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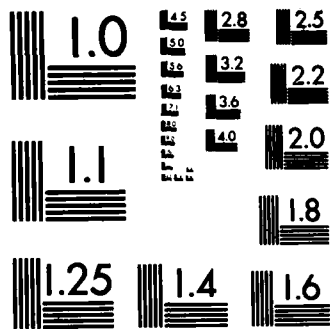
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W.W. Hansen Laboratories of Physics  
Stanford University  
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LASER PHYSICS AND LASER SPECTROSCOPY

Final Technical Report

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Robert L. Byer  
Applied Physics Dept.,  
Stanford University  
(415) 497-0226

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ABSTRACT

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## LASER PHYSICS AND LASER SPECTROSCOPY

Robert L. Byer

### I. INTRODUCTION

#### A. Review of Laser Ionization Mass Spectroscopy Research

During the past year we have completed a study of laser ionization as a source of ions for mass spectrometry. We have evaluated mass spectrometers and have identified the Fourier Transform Mass Spectrometer (F.T.M.S.) as the optimum approach for mass measurements. We have studied the F.T.M.S. approach and have designed a complete system with a potential mass resolution of 10,000 and a potential sensitivity of less than 100 ions.

The key components in the design are the laser ionization, the supersonic expansion nozzle for cooling molecular species, and a permanent magnet based F.T.M.S. with computer processing. The design of the instrument is described in Sections II and III.

At this time there is not in existence a mass spectrometer with the resolution and sensitivity features of our design. We have made theoretical contributions to mass spectrometry design in the areas of sample preparation and ionization, magnet design and data processing. Because of budget limitations we have elected not to proceed with the construction of the high resolution F.T.M.S.

This report summarizes the results of our two year theoretical study of laser ionization as a source for mass spectroscopy studies.

We have purchased the Nd:YAG laser system and have on hand a dye laser and a vacuum system. We plan to use this equipment to study laser plasma pumping of vacuum ultraviolet laser sources. A slab glass amplifier is

being constructed that will amplify the Nd:YAG output from .8 J to 6 J per pulse at 10 Hz for production of the laser plasma source. Studies are now underway to evaluate the plasma pumping of the indium ion atomis system.

#### B. Review of Single Crystal Fiber Research

During the past year we have worked toward the completion of our second generation single crystal fiber growth machine. The machine and its major components are described in Section IV.

We have continued to work closely with the Center for Materials Research Thrust Effort and to assist with improvements in the first growth machine. These improvements include better focusing optics, the addition of an optical attenuator for improved laser power control and the addition of an environmental chamber around the growth region. The improvements have led to single crystal fibers with reduced diameter fluctuations.

Recent growth of sapphire fibers have demonstrated that the new machine produces high quality fibers. We have grown over 20 fibers near 170  $\mu\text{m}$  diameter. These fibers have 1% diameter variations and are significantly better than earlier fibers grown on the first generation machine.

We have also analyzed nonlinear interactions in single crystal fibers and hve planned a strategy for implementing nonlinear interaction studies. We plan to study stimulated Raman scattering in  $\text{Li}_2\text{GaO}_3$  fibers because the Raman process does not require phasematching and  $\text{Li}_2\text{GeO}_3$  does not require poling. We then plan to study mixing in  $\text{LiNbO}_3$  fibers and at the same time study the poling problem. Second harmonic generation, which has the most sensitivity to phasematching will follow. We have on hand a 0.8  $\mu\text{m}$  diode laser source which eventually will be frequency doubled in  $\text{KNbO}_3$  fibers. We have also considered parametric oscillation in  $\text{LiNbO}_3$  fibers and infrared and sub-millimeter wave generation in  $\text{LiNbO}_3$  fibers.

The rapid growth rate of fibers allows preparation of new crystalline materials such as laser host crystals at very low cost. We plan to use this capability to grow  $\text{GGG:Nd}^{++}:\text{Cr}^{++}$  related compounds and to study the spectroscopy of the samples as possible new laser materials.

## II. LASER IONIZATION WITH MASS SPECTROMETRY

### A. Resonant Ionization Spectroscopy

The ability of lasers to produce high intensities of narrow bandwidth light makes possible many types of selective excitation of atoms and molecules. One type of excitation, photoionization, allows detection of a target species in exceptionally small quantities due to the ease of detecting charged particles. Hurst and Payne<sup>1</sup> have shown that virtually every atomic species can be selectively photoionized using existing lasers. The processes they proposed are collectively described as "resonant ionization spectroscopy", abbreviated as R.I.S. Experiments<sup>2</sup> have demonstrated the ability to detect a single atom using R.I.S. The extension of the R.I.S. technique to molecules has the promise of allowing measurement of trace impurities or pollutants in real time. The application of such measurements include materials-science studies, basic spectroscopy and physical chemistry studies, and early warning and identification of extremely toxic substances released in industrial or in defense related situations.

### B. Extension of R.I.S. to Molecules

The use of R.I.S. with atoms is straightforward. It relies on the facts that atomic outer shell electron bound-bound transitions have narrow linewidths and that the wavelengths of transitions are like fingerprints, being different for each different atomic species. One or more tunable lasers are used to step an outer

shell electron up through bound states, until it nears its ionization potential. A strong infrared laser then photoionizes the target atom by supplying just enough energy in a single photon to remove the excited electron as shown in Fig. 1. The ionization is selective because none of the laser photons are capable of directly photoionizing any species of atom, and only one type of atom has the right absorption transitions to make the step-wise excitations needed to reach the ionization potential.

The situation is more complicated for selectively photoionizing molecules. Unlike atoms, molecules have rotational and vibrational energy levels which create extremely complicated and densely packed spectra. At room temperature the absorption aspects of most molecules become continuum absorption bands, making it impossible to select a single molecular species by laser absorption. This problem can be overcome by cooling the molecular gas sample to within a few degrees of absolute zero and thus "freezing out" the rotational/vibrational modulation of the basic electronic state spectrum. Such cooling has been widely demonstrated by the use of supersonic nozzle expansions, and the simplified spectra of some molecules near absolute zero have been obtained by spectroscopic techniques such as CARS.<sup>3</sup>

Another difficulty with molecules is not so easily solved. The multi-step excitation of an electron through its energy states is easily done in atoms because the life times of atomic states are generally comparable to the pulse width of high power pulsed

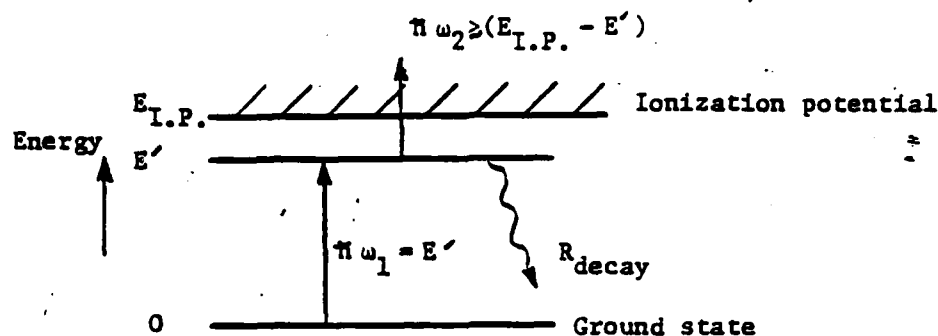


Figure 1—A laser tuned to frequency  $\omega_1$  (ultraviolet) excites an electron from an atomic ground state to a bound state of energy  $E'$ . An infrared laser of frequency  $\omega_2$  then photoionizes the excited atom at a rate much faster than the natural decay rate  $R_{decay}$ . Atoms without an excited state of energy  $E'$  will not be photoionized, so long as their ionization potential is greater than  $\pi \omega_1$ .

lasers, i.e. on the order of 1 - 10 nanoseconds. Unfortunately, the excited electronic state life times in molecules are frequently less than a picosecond.<sup>4</sup> Thus molecular levels decay before another laser photon can strike the molecule and excite the electron again to a higher level. One class of molecules, the aromatic hydrocarbons, have a structure which creates long lived excited states, and these molecules can be selectively ionized by the R.I.S. technique with presently available lasers.

The study of this class of molecules happens to be of great interest to organic chemists and to the petrochemical industry. For molecules which cannot be so selectively photoionized, useful studies can be made by combining non-selective photoionization with detection by a mass spectrometer.

### C. Mass Spectrometry

The mass spectrometer is commonly used to identify molecules in a sample of unknown composition, and may also be used to determine the quantity of the various components present. To uniquely identify molecules, the spectrometer must have sufficient mass resolution. If the mass is measured to sufficient accuracy, then it can be determined that one and only one combination of atoms could have produced the total mass of the molecule seen. However, sensitivity must remain high if quantitative measurements are to be made on trace components. For most mass spectrometers high sensitivity and high mass resolution are mutually exclusive conditions. An exception is the Fourier Transform Mass

Spectrometer (F.T.M.S.), which we judge to be uniquely adapted to use with a supersonic nozzle sample cooler and with the R.I.S. technique.

In general, mass spectrometers use combinations of electric, magnetic, or radio-frequency electromagnetic fields to separate ions of different charge-to-mass ratios. Ions may be separated in time or space, and are usually detected by physically colliding with a detector, such as an electron multiplier or photographic plate. A brief comparison of mass spectrometers for use with R.I.S. includes three commonly used types, and the relatively new type which we selected as optimal for our purposes. The common types are:<sup>5</sup>

- i. magnetic/electric sector mass spectrometer
- ii. quadrupole mass filter
- iii. time-of-flight mass spectrometer.

The magnetic/electric sector mass spectrometer is the oldest type. It is capable of high mass resolution ( $R \geq 10^5$ ), or modest sensitivity, but cannot provide both at the same time. The device has many disadvantages. To obtain high mass resolution may take a room-sized instrument with very expensive magnets. High resolution for more than one mass requires the use of photographic plates, eliminating the ability to make measurements in real time. Polyelement electronic detectors have been used<sup>6</sup> but they are difficult to engineer and degrade resolution. Furthermore, the mechanical alignment of this device is very critical and quite complicated. It is totally unsuitable for a general purpose laser ionization mass spectrometer application.

A smaller device that is capable of moderate resolution ( $R \sim 1000$ ) is the quadrupole mass filter. These devices use a radio frequency field which permits only a single mass to pass from a sample chamber to the detector region. The major disadvantage of this device is that it can only detect one mass at a time. This device might be useful for a dedicated system that looks only for a few masses.

The time-of-flight mass spectrometer (T.O.F.M.S.) is well suited for applications that do not require high mass resolution. It is a relatively compact device, rarely over a meter long, and is mechanically simple. It accelerates ions from a sample chamber and into a drift tube. Ions of different masses have different drift velocities, and, therefore, arrive at the detector at the end of the drift tube at different times. The mass resolution is limited to  $R \sim 1000$  for the ordinary T.O.F.M.S., while special types of more complex nature<sup>7</sup> can boost resolution up to  $\sim 10,000$ . Such a low resolution cannot uniquely identify very heavy molecules, but nevertheless can be useful in many situations where there is prior knowledge of the expected molecular species. One major advantage of the T.O.F.M.S. is its great sensitivity with small throughput losses even when run at maximum resolution. Another is the fact that all masses can be detected in a single ion-creation pulse.

The Fourier transform mass spectrometer (F.T.M.S.) is a newly developed technique which makes use of the ion cyclotron resonance effect to measure mass.<sup>8</sup> A uniform magnetic field is

used to force ions into cyclotron orbits of angular frequency

$$\omega = \frac{qB}{m} \quad (1)$$

where  $q$  is the ionic charge,  $B$  is the magnetic field strength and  $m$  is the ionic mass (M.K.S.) units.

The orbit frequency depends only on the strength of the field and the charge-to-mass ratio of the ion and is totally independent of the velocity of the ion or its radius of orbit. The orbiting ions create a rotating dipole moment which radiates a sinusoidal signal at its frequency of orbit.<sup>9</sup> This radiation is detected, allowing a mass measurement to be made without physical contact between the ions and the detector. Resolutions greater than  $10^6$  have been achieved and unlike most spectrometers, there is no limitation on the ultimate achievable resolution other than the time spent in observing the circulating ions. This is made clearer in the section dealing with the Fourier transform aspects of the F.T.M.S. Additional advantages of the F.T.M.S. include its small size and mechanical simplicity and the fact that its data acquisition method is inherently suited to computer manipulation and real time studies.

### III. THE FOURIER TRANSFORM MASS SPECTROMETER

#### A. Basic Principles

Mass spectrometer using the ion cyclotron resonance (I.C.R.) principle first appeared in the 1960's and underwent many changes before the concept of the Fourier transform mass spectrometer was

proposed by Comisarow and Marshall in 1976.<sup>10</sup> Ions are created inside a "trapping cell"<sup>11</sup> which is immersed in a uniform magnetic field B. The cell consists of a rectangular metal box whose sides produce an electrostatic potential well. This electrostatic potential, in conjunction with the magnetic field, prevents the escape of the ions from the central region of the cell. The sides of the trapping cell are electrically isolated, and a pair of opposing sides may be driven by a signal generator at the I.C.R. frequency of the ion under consideration, (Eq. 1). The ion absorbs energy just as in a normal cyclotron, expanding its orbital radius as it does so. If the signal generator is then turned off, and a sensitive amplifier is connected to the pair of opposing plates, then the circulating ions generate a sinusoidal voltage across those plates at the I.C.R. frequency.<sup>12</sup>

The mass resolution R is, by definition

$$R = \frac{m}{\Delta m} \quad (2)$$

where  $\Delta m$  is the full width at half maximum of the plot of signal output as a function of mass m. By differentiating Eq.(1) it is easily shown that

$$\begin{aligned} R &= \frac{m}{\Delta m} \\ &= \frac{qB}{m\Delta\omega} \\ &= \frac{\omega}{\Delta\omega} \end{aligned} \quad (3)$$

where  $\Delta \omega$  is the full width at half maximum of the plot of signal output as a function of angular frequency  $\omega$ . Thus mass resolution is conveniently equal to the frequency resolution of the instrument. The result is that the mass resolution is limited only by the ability to accurately measure the I.C.R. frequency, which in turn is basically limited by the time spent observing the signal, according to the theory of Fourier transforms.<sup>13</sup>

Consider now the case where more than one mass species is present in the spectrometer. First, all species must be excited into cyclotron orbits. The techniques for doing this are discussed in the next section. Once excited, the ions generate a complicated output signal which is the superposition of the sinusoidal signals generated by each different mass. By applying a Fourier transform to the detected time domain signal the frequency spectrum is generated. This, by Eq.(1), is tantamount to obtaining the mass spectrum of the sample.

To briefly review Fourier transforms<sup>14</sup> consider a signal  $G(t)$  which is function of time  $t$ . This signal (the output of the mass spectrometer) is a superposition of sinusoidal components:

$$G(t) = \int_0^\infty A(\omega') \cos(\omega' t) d\omega' + \int_0^\infty B(\omega') \sin(\omega' t) d\omega' \quad (4)$$

where  $A$  and  $B$  are coefficients that may be obtained by the Fourier transforms

$$A(\omega) = 1/\pi \int_0^\infty f(t) \cos(\omega t) dt \quad (5a)$$

$$B(\omega) = 1/\pi \int_0^\infty f(t) \sin(\omega t) dt \quad (5b)$$

Let us now define the coefficient

$$C(\omega) = [ (A(\omega))^2 + (B(\omega))^2 ]^{1/2} \quad (5c)$$

We call  $A(\omega)$ ,  $B(\omega)$ , and  $C(\omega)$  the absorption, the dispersion and the magnitude spectra, respectively. The values of  $A$  &  $B$  change if we change the phase of the function  $G(t)$ , (i.e. if we shift the origin defined as  $t = 0$ ), but the value of  $C(\omega)$  is independent of phase. It is the magnitude spectrum that is most easily interpreted as showing the frequencies present in the original signal  $G(t)$ , and hence the masses present. With proper acquisition of the mass spectrometer signal, the value of  $C(\omega)$  is directly proportional to the number of ions having I.C.R. frequency.<sup>15</sup>

Detailed calculations of the output signal and its Fourier transform<sup>16,17,18</sup> have been carried out and show many interesting results. First, the mass resolution can be expressed in terms of the observation time. However, the observation time may be limited by one of two constraints:

- i. in the "high pressure" limiting case, the ion orbits decay exponentially with time due to collisions with background gas molecules in the ion trapping cell,
- ii. in the "low pressure" limiting case, the ions orbit "indefinitely", (as long as several minutes), and the observation time is limited by convenience.

For the high pressure limit, Comisarow and Marshall<sup>19</sup> show that 95% of the theoretical maximum resolution can be achieved if we observe the signal for  $t = 3\tau$ , where  $\tau$  is the decay time constant of the signal. In the low pressure case, the resolution improves linearly with the observation time, i.e.

$$\text{Low pressure limit: } R = (1.272 \times 10^6) \frac{qBT}{m} \quad (6a)$$

$$\text{High pressure limit: } R = (2.784 \times 10^6) \frac{qB\tau}{m} \quad (6b)$$

where  $q$  = charge in multiples of  $e = 1.6 \times 10^{-19}$

$B$  = magnetic field in K Gauss

$m$  = mass in a.m.u.

$T$  = observation time in seconds

$\tau$  = exponential decay time constant of signal

In practice, a continuous recording of the signal  $G(t)$  followed by the application of the integral equation (Eq.5) to determine  $C(\omega)$  is not done. Instead, an analog-to-digital converter (A.D.C.) is used to sample the waveform  $G(t)$  at uniform time increments. The number of discrete data points  $N$  taken is related to the observation time  $T$  and to the frequency  $F$  at which the A.D.C. samples the data by

$$N = T F. \quad (7)$$

Furthermore, Fourier transform theory shows that at a sampling rate  $F_{\text{Nyquist}}$  (the "Nyquist rate"), the highest frequency allowed to appear in the signal  $G(t)$  is  $\frac{1}{2} F_{\text{Nyquist}}$ . The highest frequency appearing in  $G(t)$  is determined by the smallest measured mass,  $m_{\text{min}}$  from Eq.(1).

If one specifies a resolution  $R$  desired for given mass  $m$ , then Eqns. 6 & 7 may be solved for the time  $T$  one must observe the signal, and the number of data points  $N$  which must be taken.

The sampling process in turn requires sufficient computer memory to store the digitized signal. The required number of bytes of memory depends on how many bits of information are used for each data point. A fast Fourier transform (F.F.T.)<sup>20</sup> is then used to find the frequency spectrum from the set of discrete data points. This transform may be done by software on a general purpose computer, or by a dedicated hardware unit. Done by hardware, high resolution mass spectra can easily be processed at the 10 Hertz rates common to pulsed Nd:YAG laser systems. General purpose computers are much slower than hardware units for computing F.F.T.'s, but at modest resolution (higher than a T.O.F.M.S. but lower than limits of the F.T.M.S.) even a small laboratory computer can produce mass spectra at a 1 Hertz rate. For many scientific studies or for pollution monitoring, such a rate would be adequate.

#### B. Design Considerations for a F.T.M.S. to be Used with L.I.M.S.

There are many basic constraints on the design of a practical F.T.M.S. intended to be flexible enough to be used in a variety of experiments. The magnet producing the uniform magnetic field should be as small and inexpensive as possible. The field strength is not arbitrary: it must yield I.C.R. frequencies which are easily worked with over the entire range of masses to be studied.

The minimum mass is determined by the highest rate at which the signal is digitized, which in turn is determined by cost considerations. The maximum resolution depends on the amount of computer memory available for signal recordings as shown by Eqs. 6 & 7. There are tricks which allow high resolution to be obtained over a narrow mass range, as discussed below. Another constraint is the speed at which the information can be processed by the data handling system, which in turn determines the repetition rate at which mass spectra may be taken. Further considerations about the gas sampling system and vacuum requirements are discussed in Section C.

1. Magnet Considerations. Sharp, Eyler and Li<sup>21</sup> considered the perturbed cyclotron motion of an ion trapped in a cell as described in reference 11. They found that the length of time an ion would stay trapped was proportional to the square of the magnetic field strength. Thus the ultimate resolution capability, which is proportional to the time over which the ions can be observed, is also proportional to the square of the magnetic field. While this argues for as strong a field as possible, and some experimenters are now using fields of 10 Teslas and larger, there are many reasons for keeping the field strength  $\sim 1$  Tesla. As a rough rule of thumb, magnet cost and size increases as the square of the field. Also, higher fields generate proportionally higher I.C.R. frequencies, which can become prohibitively expensive to digitize due to the high sample rates needed. For an F.T.M.S with

laser ionization, we feel that 1 Tesla is sufficient. Early experiments with I.C.R. mass spectrometers demonstrated that such fields could yield resolutions of at least 250,000 at a mass of  $\sim 28$  amu.<sup>22</sup> Such resolution is sufficient for unambiguous elemental composition determinations of organic molecules weighing up to  $\sim 200$  amu.

Having decided on the approximate field strength for our experiments, we next considered the type of magnet to buy. The types examined were:

- i. conventional laboratory electromagnet with iron poles (commercial)
- ii. custom built iron poled electromagnet,
- iii. superconducting solenoidal magnet with open air bore,
- iv. conventional solenoidal electromagnet,
- v. permanent magnet with iron poles.

Early experimenters in I.C.R. spectrometry used conventional laboratory electromagnets. An example of a currently available magnet of this type is the Varian model V-7202 magnet with 9 inch pole faces. This magnet, together with its 8 kilowatt power supply, weighs  $\sim 2,200$  pounds and occupies a significant amount of laboratory space. It requires large amounts of power and cooling water. We found this type of magnet to be too large physically. At a cost of up to \$30,000 it was no less expensive than any other solution. The same basic conclusion was reached regarding a custom built iron poled electromagnet which could have been designed and built at the Stanford Linear Accelerator Center.

A superconducting solenoidal electromagnet with an air bore requires far less electrical power, and is capable of very high field (10 Tesla and greater), but was judged far too expensive. Cost would be at least \$60,000 for even a magnet of the 1 Tesla size with a bore large enough for the F.T.M.S. ion cell and vacuum system. However, these magnets are now being used by I.C.R. experimenters such as McIver<sup>23</sup> to achieve extremely large fields ( $\sim 32$  Teslas) for extreme high resolution work. (This work is not using the F.T.M.S. technique, however, instead a marginal oscillator is used to detect the presence of a single desired mass).

Consideration of Eq.1 & 3 show that the mass resolution as a fraction of the observed mass, cannot be any better than the homogeneity of the magnetic field over the volume in which the trapped ions can move because the I.C.R. frequency  $\omega$  is proportional to the field  $B$ . In the search for high homogeneity magnets we considered solenoidal coil electromagnets of the type developed for medical nuclear magnetic resonance (N.M.R.) imaging of whole human bodies.<sup>24,25</sup> Although these magnets have been developed with homogeneities of 3 ppm over a spherical volume of 10 cm radius it is impractical to obtain the field strength desired with reasonable power consumption because these magnets use no iron to concentrate the magnetic flux lines. It is the absence of magnetic materials that simplifies the design of these magnets to high field homogeneity.

The most desirable magnet for our instrument was found to be a permanent samarium/cobalt magnet with iron pole pieces. Because the technology of Sm-Co magnets is relatively new, no large dipole magnet of the type we desired has ever been built. Working with a supplier of custom permanent magnets<sup>26</sup> we arrived at a design with many attractive features. The magnet is only one cubic foot in volume and weights only 400 pounds, but would provide a 1 Tesla field homogeneous to one part in 10,000 or better over a cube shaped volume with one inch sides. The gap between the pole faces is two inches, enough to fit the ion trapping cell and its vacuum jacket. The permanent magnet has no field fluctuations due to power supply instabilities, nor does it need any external power supply or water cooling. Its use would make a portable F.T.M.S. instrument feasible. The price quote was ~\$29,000 for the design and construction of the magnet.

2. Electronics and Signal Processing. One of the interesting aspects of the F.T.M.S is that the mechanical part of the instrument is extremely simple, consisting mostly of the ion trapping cell, a vacuum system, the sample introduction system (a supersonic nozzle), and a magnet. The real heart of the system is the electronics and signal processing procedures. Specifying this part of the system to a large extent specifies the capabilities of a particular F.T.M.S.

For the selected magnetic field to be 1 Tesla the frequencies that we must deal with are fixed according to Eq.1. Hydrogen atoms have the highest I.C.R. frequency of 14 MHz, and thus require

sampling at a rate of 28 MHz according to the Nyquist theorem. A very heavy molecule, say with mass of 1,000 amu, requires a Nyquist rate of only 28 KHz. The mass range of  $\sim 1$  to 1,000 amu is sufficient for any of the experiments we considered, so we need signal processing equipment for the range of  $\sim 25$  KHz to 25 MHz.

Figures 2 & 3 show two possible signal processing schemes. The first scheme is straightforward: the I.C.R. signal is amplified, sampled by an A.D.C. and stored in a buffer memory. The buffer memory is read either by a computer or by a hardware F.F.T. processor, the F.F.T. is taken, and the mass spectrum is displayed on a C.R.T. and store on magnetic media for later examination if desired. In this scheme, resolution may be limited by the amount of buffer memory available.

The second scheme allows extremely high resolution measurements to be made over a reduced mass range. The original I.C.R. signal is heterodyned to a lower frequency by mixing with an oscillator offset frequency. This lower frequency is then sampled at its Nyquist rate, which is much slower than that for the original I.C.R. signal. Thus for a fixed number of data samples (fixed by the amount of buffer memory available), the signal may be observed (recorded) for a much longer time than would be possible without heterodyning. It can be shown that the obtainable mass resolution with this technique is just as great as if the original I.C.R. signal were recorded at its fast Nyquist

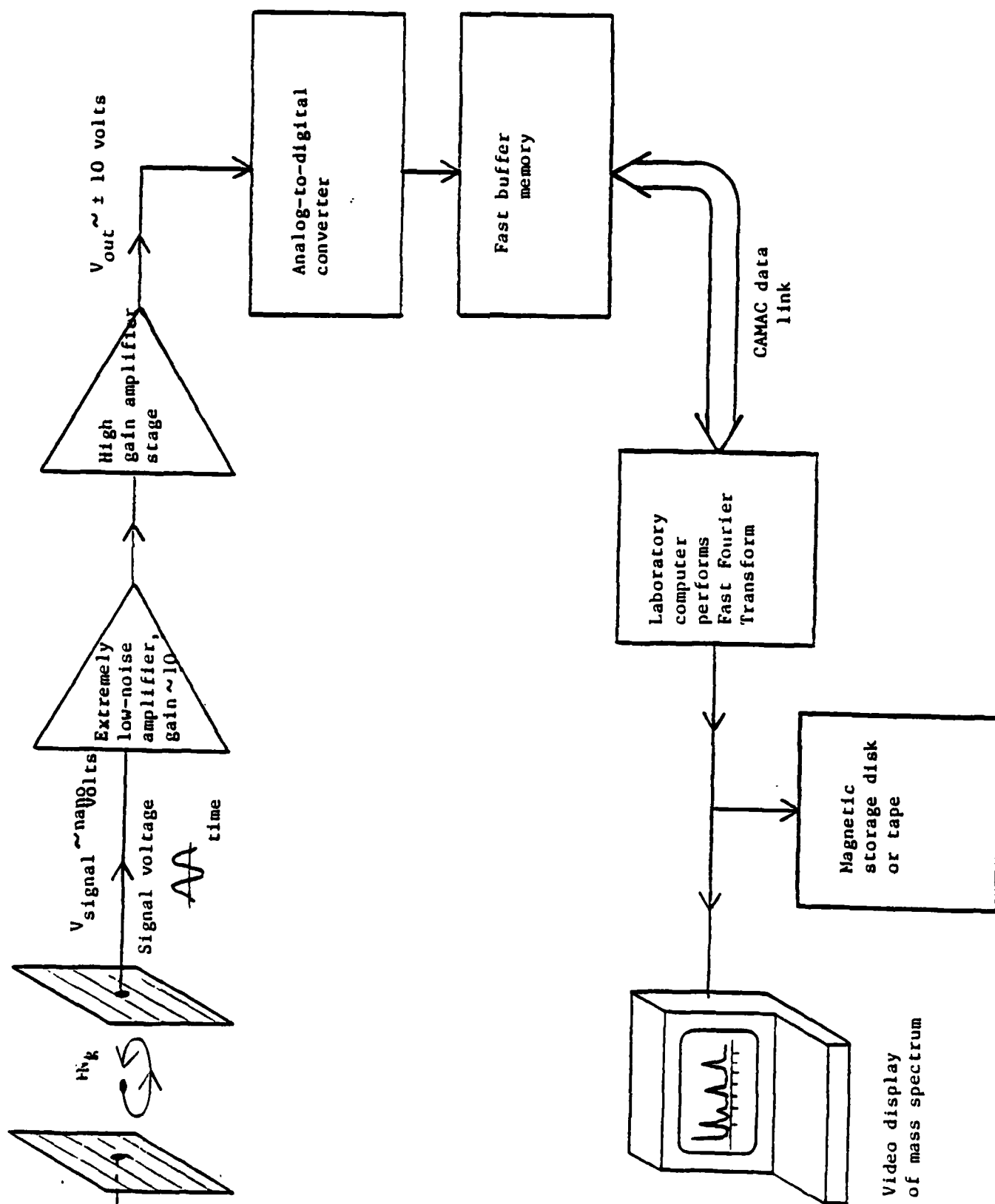


Fig. 2--Most straightforward data acquisition system for F.T.M.S.

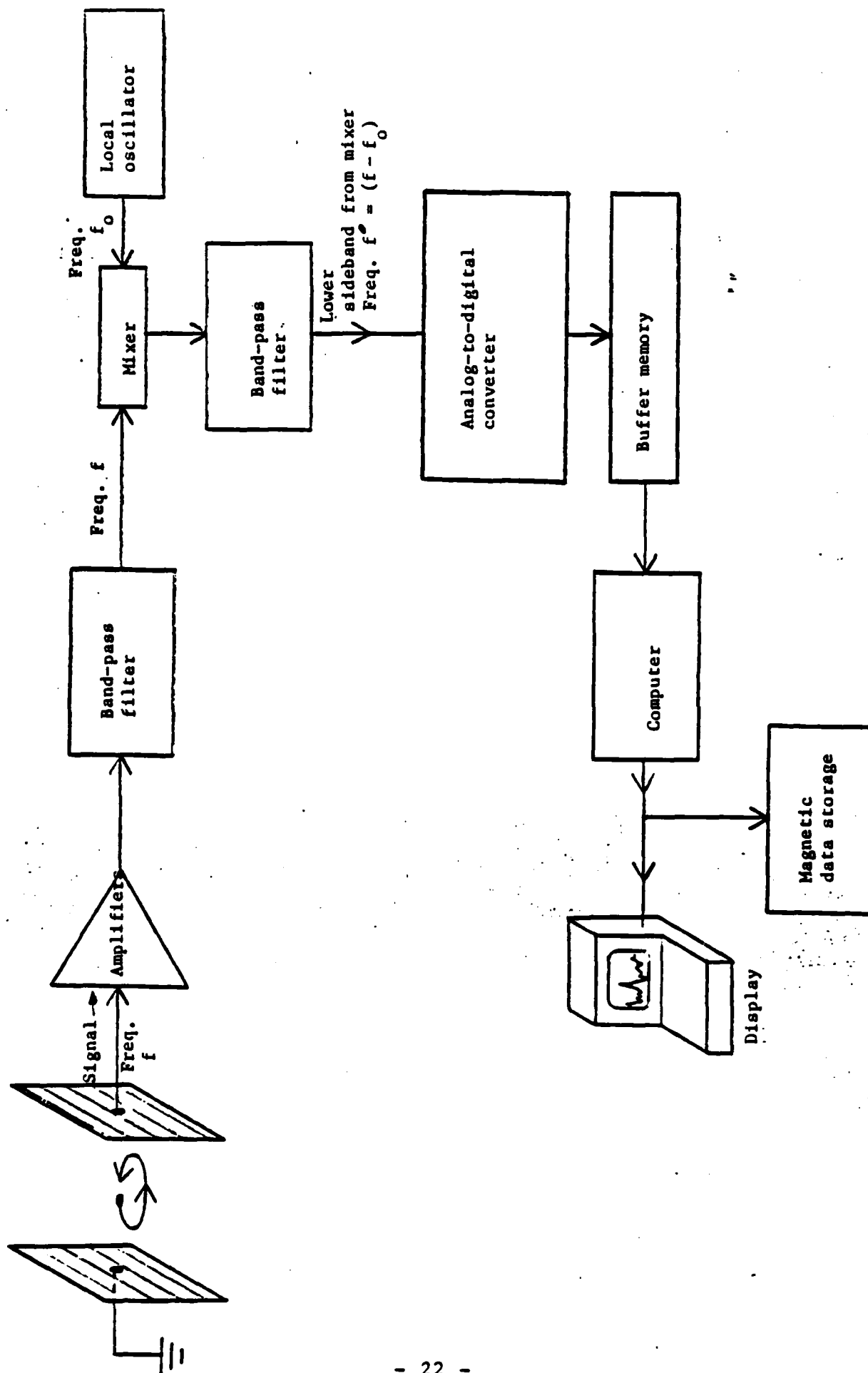


Fig. 3--Heterodyne technique for lowering the analog-to-digital data conversion rate.

rate for the long period of time.<sup>27</sup> Due to the problem of aliasing,<sup>28</sup> however, one can only look at a small range of frequencies near the oscillator frequency when using this technique. Band limiting filters must be used before the mixing operation in order to prevent aliasing. In fact, even in the first scheme, one must use band limiting filters to ensure that frequencies above the Nyquist rate do not get digitized by the A.D.C., or aliasing problems will occur.

The major components of the signal processing system are then:

- i. amplifiers to boost the I.C.R. signal to useable levels,
- ii. anti-aliasing filters,
- iii. signal generator and mixing equipment for heterodyne technique,
- iv. a fast A.D.C. with buffer memory,
- v. an interface to transfer the buffered data record to a computer,
- vi. software or hardware to perform the F.F.T. and display the mass spectrum.

Additional electronic equipment is needed to provide the ions with their original excitation into cyclotron orbits. This and the first four items listed above are discussed below. Items 5 & 6 are considered in the next section on data handling.

The first stage of amplification is the most critical. Comisarow's paper<sup>29</sup> on the signal obtained from an I.C.R. experiment provides the information necessary to specify the amplifier needs. Figure 4 shows the model of the I.C.R. signal

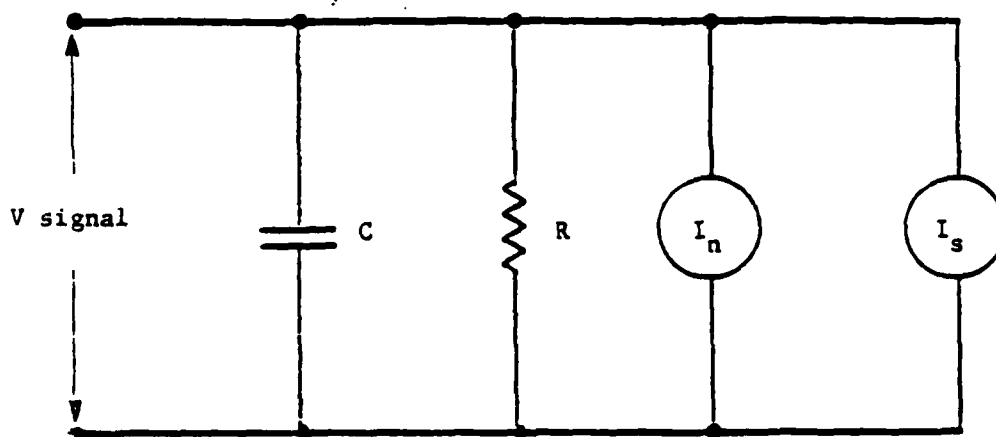


Fig. 4--I.C.R. Signal Generation. A voltage signal from the I.C.R. cell is generated by a signal current  $I_s$  and a thermal noise current  $I_n$  passing through a resistance  $R$  (the detector circuit impedance).  $C$  is the shunt capacitance associated with the I.C.R. cell, the detection circuit, and their connection.

and its detection. From reference 29 we know that the signal voltage is independent of the ion mass if the circuit is predominantly capacitive, that is if

$$\omega C \gg 1/R \quad (8)$$

A typical I.C.R. trapping cell is cubic with sides of 2 cm. Treating the pair of plates which pick up the signal as a parallel plate capacitor, the I.C.R. cell should have a capacitance of 0.18 pF. The total capacitance of the detection circuit is, therefore, dominated by the capacitance of the first amplifier stage, which can be held down to ~3 pF with good design. Since we must amplify frequencies of down to ~14 KHz, Eq. 8 tells us the input impedance  $R$  of the amplifier must be  $\gg 4 \times 10^6$  ohms. Furthermore, the signal-to-noise ratio is proportional to  $(R)^{1/2}$  and so the higher the amplifier impedance the better. The best way to achieve such a high impedance is to use a F.E.T. or M.O.S.F.E.T. input stage for the first amplifier, which should give  $R \sim 10$  Mohms.

Now the fundamental signal-to-noise ratio is

$$\frac{S}{N} \text{ voltage} = \frac{N_g^2 r B \sqrt{R}}{2 m d \sqrt{2kT} \Delta f} \quad (9)$$

where

N = number of ions                      R = detector input resistance  
q = charge                                m = ion mass  
r = cyclotron orbit radius      d = separation of detector plates  
B = magnetic field                      k = Boltzmann constant  
T = Kelvin temperature of circuit

and where the noise bandwidth  $\Delta f$  is (data acquisition time)<sup>-1</sup>

Assuming a data acquisition time of 0.1 second then  $\Delta f = 10$  Hz.

If the cyclotron orbits are 1 mm in radius, the S/N is

$S/N = N \cdot 3.88 / m(\text{amu})$ . Thus if there are as many ions as the mass in amu, the S/N remains high. However, the noise introduced by the first amplifier stage must also be considered. It is helpful to know the signal voltage<sup>30</sup>

$$V_{\text{rms}} = \frac{Nqr}{\sqrt{2} dC} \quad (10)$$

where C = circuit capacitance which for aforementioned conditions is

$$V = 2 \text{ nanovolts} \cdot N \quad (11)$$

It seems that the lowest noise level obtainable in commercial F.E.T. high bandwidth amplifier modules is  $\sim 1 - 10 \text{ nV} / \sqrt{\text{Hz}}$ .

This means that with a noise bandwidth of 10 Hz it will take  $\sim 100$  ions to give a signal level greater than the noise introduced by the amplifier. Considering that the original sample hit by the laser beams can contain  $\sim 10^{12}$  molecules we have the capability to see  $\sim 0.1$  parts per billion without special signal processing.

If a lock-in amplifier (i.e. phase sensitive detection) is used to look for one particular mass, then a single ion generating a 2 nV signal should be detectable. Thus the F.T.M.S. with laser ionization can be exceptionally sensitive.

Our conclusion is that the first amplifier stage should be a well designed, discrete component F.E.T. amplifier of input impedance  $> \sim 10$  Mohms. It should have a gain of 10 to get the signal above the noise level of the succeeding amplifier stages and must have a flat gain from  $\sim 14$  KHz to  $\sim 14$  MHz. This calls for a large bandwidth gain product (B.W.G.P.), which is not easy to achieve but which is possible. The first amplifier stage must be located very close to the I.C.R. trapping cell - within a few centimeters - to minimize microphonic noise pickup. The vacuum casing surrounding the I.C.R. cell and amplifier should be designed to also serve as RF shielding to prevent radio transmissions and other RF noise from swamping the I.C.R. signal. In addition, the amplifier must be potted to prevent virtual leaks and outgassing into the very high vacuum which surrounds it. The cost of the first amplifier stage should not exceed \$500 including the necessary vacuum package for the amplifier.

A second amplifier stage consists of two Teledyne-Philbrick<sup>32</sup> model 1443 (or similar) low noise high impedance op-amps. These have a 2 GHz bandwidth product, a 1,000 V/microsecond slew rate, and noise of  $20 \text{ nV}/\sqrt{\text{Hz}}$  above 10 Hz. They can give a voltage gain of 100 for small signals with a 20 MHz bandwidth. Thus two stages should be able to give a gain of 10,000, enough to bring the signal level up to 50 mV, as needed by the mixer section.

Finally, a third amplifier stage following the mixer must bring the signal level up to  $\pm$  10 volts to match the input requirements of the A.D.C. signal digitizer. At these large voltage levels and high frequencies, one must be very careful to stay within the slew rate specifications of the op-amps used, but low noise characteristics are no longer very important. Perhaps three stages of Burr-Brown 3554 op-amps<sup>33</sup> will be sufficient for the third stage amplifier.

The anti-aliasing filters must be adjustable high-Q band-pass filters. Wavetek-Rockland<sup>34</sup> makes filters designed for this purpose, and we suggest the model 442 tunable hi-low filters, which cover the range from 10 Hz to 1.1 MHz. No filters were found which could cover the entire frequency range we desired. Three of these filters would be required; two would be "stacked" in series before the input of the mixer to provide 48 db/octave attenuation at the high and low frequency limits, while the third filter would remove the unwanted harmonics and sidebands in the output of the mixer. Additional low cost high-Q fixed bandwidth filters could be used as needed for particular experiments requiring the heterodyne technique at frequencies above 1.1 MHz (i.e. for masses below 12.6 amu). Because of the low masses involved the resolution obtained without the heterodyne technique should be quite sufficient to make unique elemental composition determinations. Thus the 1.1 MHz upper limit of the tunable filters should not present any problems.

The next items on the list of required electronics are the signal generator and mixing stage used for the heterodyne technique. In order to make the F.T.M.S. quite flexible under computer control, it is desirable that the signal generator be programmable. The clear choice among all programmable frequency generators on the market as of mid-1982 is the Wavetek-Rockland model 5100-13, which synthesizes frequencies from DC to 3 MHz with 0.001 Hz resolution.

The mixing stage can be commercially obtained from Mini-Circuits Inc.,<sup>35</sup> as an "RF mixer module". These are available in a very wide range of specifications and are quite inexpensive (~ \$50).

Next to the amplifiers the most critical electronic system contained in the F.T.M.S. is the signal digitizer. We require a maximum digitizing rate of 25 MHz and must be able to digitize at slower rates, preferably under computer control. We also need several thousand words of buffer memory which can be read into a general purpose laboratory computer at rates fast enough to run experiments in real time at ~1 - 10 Hz repetition rates. There should be at least 8 bits of resolution in the digitizing process so that quantitative measurements of a sample composition may be accurately made. A system providing all of the above requirements is the LeCroy model TR8837 2-channel, 25 MHz waveform analyzer with 16K words of memory.<sup>36</sup> This comes as a CAMAC module, which makes computer interfacing relatively easy. The cost is ~ \$6,000. In addition, a CAMAC controller providing direct memory access (D.M.A.) to our computer is necessary. These are available for DEC PDP-11 computers from Kinetic Systems.<sup>37</sup>

The last electronic system to be discussed in this section is that which provides the ion excitation. The simplest method would be to apply a sinusoidal voltage across a pair of opposing plates in the I.C.R. trapping cell. This, however, would excite only one mass into cyclotron orbits, namely that mass having cyclotron frequency equal to the applied frequency. In order to excite all masses there are two methods which may be used. One commonly referred to in the literature is the "frequency chirp" method. A frequency chirp is a sinusoidal signal of time varying frequency, such as the function

$$G(t) = \sin[(\omega_0 + \omega' t)t]$$

which starts with frequency  $\omega_0$  and ends with frequency  $\omega_0 + \omega' T$  at time  $T$ . This would be a linear frequency chirp, since the frequency increases linearly with time. Such a signal can excite all ions having masses with resonant frequencies which occur during the chirp.<sup>38</sup> However, one must be cautious when using this technique, as described in the reference.

All masses receive some excitation from the chirped drive signal, but do not receive an equal amount of excitation, nor is there a simple function for predicting the amount of excitation a particular mass receives.

This is undesirable if one wishes to make quantitative measurements of the amount of a given mass of ion contained in the sample. Fortunately, there is another method of excitation which is made possible by the use of lasers to perform the ionization inside the I.C.R. cell.

The method we propose for exciting the ions into large cyclotron orbits is an impulse excitation. From Fourier transform theory it is known that a function which has a narrow peak of width  $\Delta t$  in the time domain must contain an approximately equal amount of all frequencies up to  $\omega \sim 2\pi/\Delta t$ . These frequency components of a sharp, impulsive voltage applied to the I.C.R. cell drive plates excite all the masses with resonant frequencies below the value  $\sim 2\pi/\Delta t$ . Put another way, if the voltage spike applied to the drive plates is short compared to the orbital time of the fastest ions, then all ions are accelerated by the electric field created by the drive impulse, but no ion is turned in the magnetic field so that it must work against the driving electric field. This technique requires all the ions to be accelerated to be localized in a small packet at the time of the impulse excitation, and that they be moving in the same direction at the start of the impulse. This is guaranteed if the ions are created at the intersection of a molecular beam and a focussed laser beam at right angles to the molecular beam. Calculations show that impulse excitation has the great advantage that it introduces no mass discrimination into the F.T.M.S. That is,

an impulse excitation can be shown to give every mass an equal orbital radius. Since the detected signal is dependent on orbital radius as per Eq.(10), an ion gives the same signal voltage regardless of its mass. As an example, for a field of 1 Tesla and I.C.R. cell plate separation of 2 cm, an impulse of 800 volts applied for 25 nanoseconds excites ions of all masses greater than 8 amu into 1 mm radius orbits, which is about the desired orbit size. Pulse forming electronics should be easily designed to provide such an impulse. A note of caution about the impulse method is that the molecular beam imparts roughly sonic velocities to the ions before any excitation takes place. To prevent mass discrimination, the impulse excitation must give all ions orbital radii very much greater than that due to their original velocity, which is mass dependent.

3. Data Handling. A great advantage of the F.T.M.S. over other mass spectrometers is its ability to generate an entire mass spectrum with each cycle of operation. These cycles can be performed at rates much higher than the 10 Hz limit imposed by our laser sources. The result is that data are generated at a tremendous rate and one must be careful to ensure that the data handling system is capable of keeping up with the high generation rate.

To start, we must specify the number of words of data that must be taken to produce each mass spectrum. This number is dictated by the mass resolution desired as per Eqs. (6 & 7). For ease of computing the F.F.T. the number of words in a data record should be a multiple of 2. Depending on the resolution desired, and on whether or not the heterodyne technique is used, the number of

words is ordinarily between 1k words and 8k words. The LeCroy waveform digitizer mentioned earlier is capable of transferring 8k words (8 bits each) to the main memory of a PDP-11 laboratory computer in 0.01 to 0.014 seconds by D.M.A. transfer. Thus there is no trouble taking data at a 10 Hz rate. This data may be transferred onto magnetic storage media, (Winchester disk, magnetic tape, floppy disk), for later evaluation, or it may be processed in real time if an F.F.T. hardware processor is used. If computer software is used to perform the F.F.T. then real time operation would probably be slowed to  $\sim 1$  Hz. If low mass resolution is sufficient, then data records of 256 or 512 words could be used. significantly speeding up software performed F.F.T.'s.

After the mass spectrum is calculated, the data should be compressed to a few hundred words per spectrum by retaining only information on the masses present and their relative peak heights, along with a heading describing the experimental conditions under which the spectrum was taken. Such a data reduction step is quite necessary, as an 80k word/second data rate would fill even a 30 megaword Winchester disk in less than a minute.

If one wishes to do the F.F.T. by software, the best alternative would be to obtain a "canned" (pre-written by experts), program. The F.F.T. is such an ubiquitous method that commercial programs are available for a variety of computers and operating systems. A good program might also be available from the computer science department of any good university. The least expensive way to obtain a hardware processor is probably to have

one custom built based on the principles outlined by Groginsky.<sup>39</sup> A general purpose commercial processor usually contains many features that are not required for the F.T.M.S. data handling and these features raise the cost of the processor.

### C. Pulsed Supersonic Jet and Vacuum System

As mentioned in the section on resonant ionization mass spectrometry, it is desirable to cool the sample molecules as much as possible in order to simplify their absorption spectra. This is best achieved by injecting the sample molecules into a carrier gas which then expands through a supersonic jet. In more precise terms, what we call a supersonic jet is known as a "continuum free jet" in the language of gas dynamics. A continuum free jet occurs when a laminar flow of gas (at densities high enough to be considered a continuous medium), is allowed to suddenly expand without constraint into a vacuum. Collisional processes which occur during the expansion process leave a core of supercooled molecules travelling along the axis of the molecular beam.<sup>40</sup> This core of cold gas is highly directional and collision-free after it has travelled a distance of a few nozzle diameters away from the nozzle exit. Formulas exist for the gas density and mass flow rate at a given distance from a free expansion nozzle.<sup>41</sup> It is possible also to predict the extent to which a particular type of gas is cooled in the expansion. Computer fitting routines done by Gustafson<sup>42</sup> allow the calculation of other parameters of the flow, such as Mach number, velocity and flow direction at any point in the flow.

Knowledge of the mass flow rate from a supersonic jet is necessary to calculate the loading on the vacuum system of the F.T.M.S. It is important to keep the background pressure inside the I.C.R. trapping cell as low as possible, so that the ions trapped inside have long trapping times. Some special experiments, which observe chemical reactions taking place between trapped ions may run at pressures up to  $10^{-4}$  torr,<sup>43</sup> but it is generally necessary to maintain a pressure of no greater than  $10^{-6}$  torr inside the I.C.R. cell. Our own desire is to achieve pressures between  $10^{-7}$  -  $10^{-8}$  torr.

One way to reduce the size of the vacuum pumps required is to use a supersonic nozzle with a valve which only emits short pulses of gas, say from 50 to 150 microseconds long. It is important that the pulses are not shorter than this, so that the supersonic flow has time to properly establish.

To achieve the desired low pressure requires a vacuum system shown schematically in Fig. 5. Such an arrangement has been used by Smalley<sup>44</sup> in conjunction with a T.O.F.M.S. In this arrangement, two skimmers isolate the I.C.R. cell chamber from the large amounts of gas flowing from the supersonic jet. Only the innermost core of cold gas is allowed to travel into the I.C.R. cell where a laser beam can ionize the target molecules. Because the jet of sample gas is a short pulse, the molecules which are not ionized by the laser continue on their straight path out of the I.C.R. cell, leaving behind only the ions which are trapped by the magnetic field. This should allow lower pressures to be achieved in the I.C.R. cell than pressures

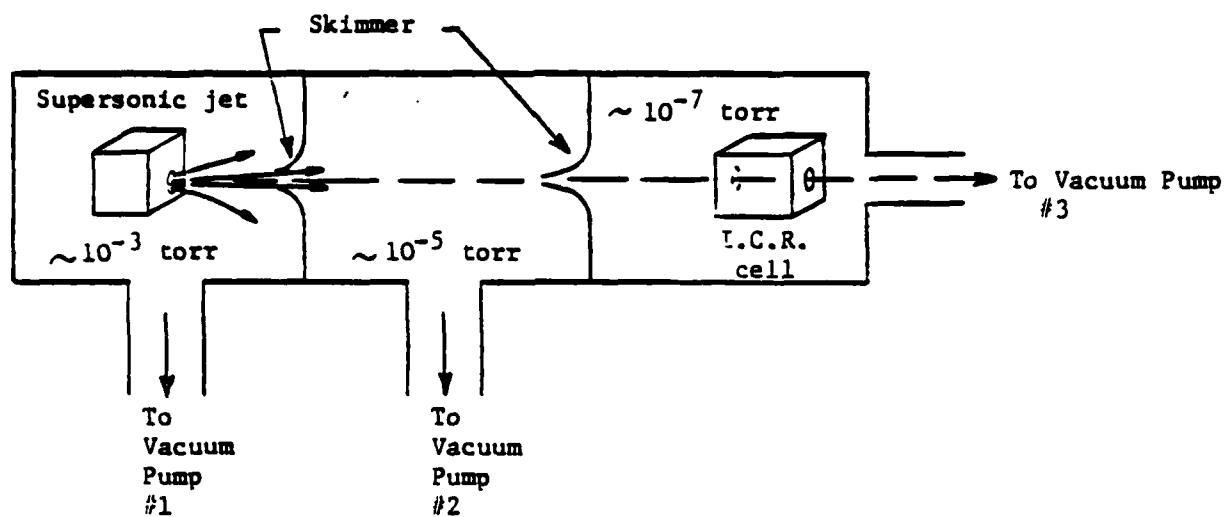


FIG. 5--Differential pumping vacuum system for F.T.M.S.

required for electron beam ionization inside the cell. In addition there is no way to remove unwanted background gas if electron beam ionization is used instead of laser ionization.

It is possible to calculate the time dependent pressures in each of the three chambers, taking into account the amount of gas introduced into each by the pulsed supersonic jet. Gas leakage between chambers through the skimmer orifices must also be considered. General observations for obtaining the lowest pressure in the I.C.R. chamber are listed below. First the skimmer orifices should be small, no greater than 1 mm, to minimize leakage between chambers. The volumes should be kept as small as possible to make the pump down time smaller than the time between gas pulses, and every effort must be made to keep the conductance to each vacuum pump as large as possible. The supersonic nozzle should be carefully located relative to the first skimmer and the walls around the nozzle, to prevent gas reflection into the jet leading to shock waves which may re-heat the sample gas.

Due to the extreme sensitivity of the mass spectrometer great care must be taken to insure that the vacuum in the I.C.R. chamber is a very "clean" vacuum. No oil backstreaming can be tolerated if a diffusion pump is used, so a liquid nitrogen cold trap must be used and well maintained. Or, alternative pumps might be used, such as a turbomolecular pump or a cryopump, to insure a clean vacuum. Note that if a cryopump is used the carrier gas cannot be helium due to the inability of the cryopump to pump this gas. In this case a nitrogen carrier is recommended.

#### D. Research Effort Progress

In personal communications with R.E. Smalley,<sup>45</sup> it was learned that a research division of Exxon near Houston, Texas, is beginning to build a similar instrument to the one designed here at Stanford. They intend to concentrate their efforts on the aromatic hydrocarbons, which is the only class of molecules for which resonant ionization spectroscopy is known to work. Due to the resources which we expect Exxon to put into this effort and due to the relative lack of understanding of organic chemistry in our laboratory group, we felt that it was unwise to concentrate so much of our resources on a project which was likely to always be "two steps behind" the Exxon group's work. We felt it better to use our resources in areas of research more likely to produce original results, and hence have decided to concentrate our work on laser plasma pumping of ionized indium as a novel vacuum ultraviolet laser source. (see Section V).

E.

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#### IV. SINGLE CRYSTAL FIBER RESEARCH

##### A. Introduction

The major part of this project is concerned with the growth of single crystal fibers, the evaluation of their linear and nonlinear optical properties, and the development of optical and nonlinear fiber devices. The unique combination of single crystal material properties and fiber geometry offers intriguing capabilities in a variety of optical devices. Three materials successfully grown at Stanford typify the broad range of potential applications. The large nonlinear coefficients of  $\text{LiNbO}_3$  suggest a number of modulators, signal processors and parametric sources.

Miniature lasers made from Nd:YAG fibers have been known for several years. Nd:YAG fibers might also be used as in-line amplifiers in conjunction with conventional glass fiber systems. Sapphire's high melting point, mechanical strength, resistance to chemical attack and favorable optical and thermal properties make it an excellent candidate for monitoring temperature or optical radiation in hostile environments and for guiding high power optical beams.

The efficient realization of these devices, particularly those involving parametric processes, requires the growth of fibers with good optical and structural uniformity and the ability to launch and preserve low order propagation modes.

In the past year we have followed two approaches towards achieving these goals. We have continued to make improvements on the first generation single crystal fiber growth apparatus at the Stanford Center for Materials Research, and we have worked toward completing our own second generation device. Successful fiber growth has been delayed by equipment problems, but both efforts are now coming to fruition.

### B. Overview of Growth Progress

The growth technique used in both the first and second generation apparatus is known as miniature pedestal growth. The tip of a small diameter (0.5 - 1 mm) source rod is melted with a focused CO<sub>2</sub> laser beam as shown in Fig. 6. A seed is dipped into the melt, forming a surface tension supported growth zone. The seed crystal is withdrawn at a constant rate to pull a crystal fiber from the melt. The diameter reduction from rod to fiber is determined by the ratio of seed to source speed.

In its first year of operation the C.M.R. machine was used to grow a variety of oriented refractory oxide fibers, including Nd:YAG, sapphire, lithium niobate, gadolinium molybdate and calcium scandate. Fiber diameters ranged from 500 down to 35 microns, in lengths up to 15 cm. Typical growth rates are 1 - 10 mm/min.

The major problem addressed in the past year was reduction of the unacceptably large variations in the fiber diameter. These were typically 5% - 10% over 5 mm lengths of larger diameter fibers, and considerably worse for longer or smaller (200  $\mu$ m) fibers. Diameter variations affect fiber performance by causing mode conversion, radiation loss and variations in modal propagation constants. Mode conversion and radiation loss are problems in any device application. Parametric devices suffer the additional problem of diameter induced phase mismatch. The criteria for adequate diameter control depends on the type of device to which the fiber will be applied, the frequency of periodic variations, the statistics of random variations, the radius of the fiber, the core to cladding index difference and the circumferential dependence of the diameter variation.

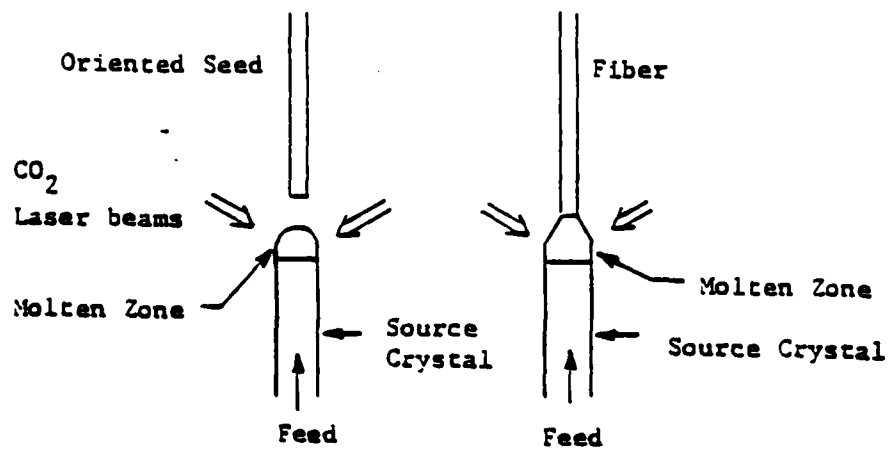


FIGURE 6

Our calculations show that for typical parametric device applications in a fiber with a non-diffused cladding, pure diameter variations will have to be held in the range 0.1 - 1% for efficient operation.

In the first year of the present contract, we identified several components of the C.M.R. apparatus that were the cause of diameter variation.

A primary source of diameter fluctuations is the focusing system used to direct the  $\text{CO}_2$  laser beam into the growth zone. The beam is split into two equal parts and focused onto opposite sides of the fiber with two 5 inch focal length lenses. The assymetric heating of the melt zone and the 1 mm square source rods conspire to produce an uneven temperature distribution and unstable growth. In addition, the minimum focal spot size of  $\sim 250 \mu\text{m}$  leads to a melt zone considerably longer than the optimum (2 - 3 fiber diameters) when growing small diameter fibers.

The feed and pull mechanisms were also implicated in the diameter control problem. The fiber and source rods are chucked to lead screws, which are driven by tachometer stabilized d.c. motors. Since the point of support of the fiber moves farther from the molten zone the longer the fiber grows, the mechanical stability of the growth zone is not optimal. This problem is particularly apparent in small diameter fibers and was amplified by the lack of a chamber to completely isolate the growth zone from the environment.

The higher frequency diameter variations are probably associated with laser power fluctuations, particularly when the laser is operated near threshold during small diameter fiber growth. Our theoretical analysis of the fiber system thermal response indicates time constants of 0.1 - 0.01 second can be expected, which is consistent with the periodicity of the observed diameter variations. We have incorporated a feedback system to stabilize the laser power, but it is limited by the slow time constant of the thermal detector used to monitor the laser output.

### C. Current Progress

As discussed in the introduction, we have addressed the problem of achieving stable fiber growth in two ways: design, construction and characterization of a second generation growth apparatus, which has occupied most of our time over the past year, and continued cooperation with the C.M.R. group in improving their growth station.

1. Second generation growth apparatus. At the end of the first year of the contract we had completed a conceptual design of a second generation growth apparatus that utilized the same basic growth technique as the first generation device, but incorporated refinements in many of the sub-systems.

One of the most important features of the new design is a novel optical system for focusing the  $\text{CO}_2$  laser beam onto the fiber in a  $360^\circ$  symmetric distribution, illustrated in Fig. 7. The optical elements are all diamond turned copper with a gold coating. The near diffraction limited  $f/2$  optics allow a focused spot as small as 30 microns, important for well controlled growth of small diameter fibers. In order to achieve good optical performance, it is critical that the two cones of the reflaxicon be accurately aligned with each other. Together with the diamond turning contractor we arrived at a mating surface design that centers the two cone axes within 1 micron. The symmetric energy distribution achieved with these optics alleviates the problem of cold spots that plague the C.M.R. system.

Another significant improvement in the second generation system is the fiber and feed rod translation devices. The lead screw and chuck of the C.M.R. device have been replaced with a belt drive system, illustrated in Fig. 8. The fiber is driven by a belt, which in turn is driven by a d.c. motor that is encoded and phase-locked to a stable reference frequency. A V-groove etched in silicon and overcoated with  $\text{SiO}_2$  captures the fiber to prevent

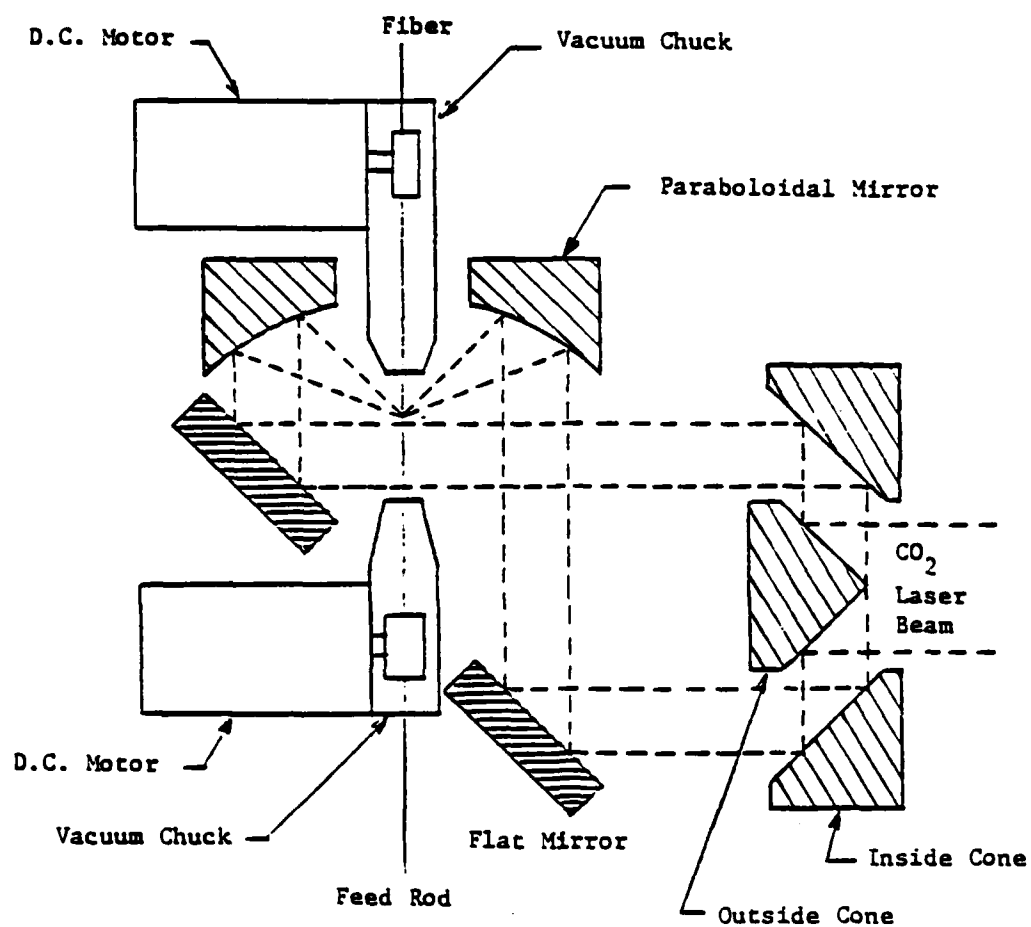


FIGURE 7

# SCHEMATIC OF FIBER TRANSLATOR

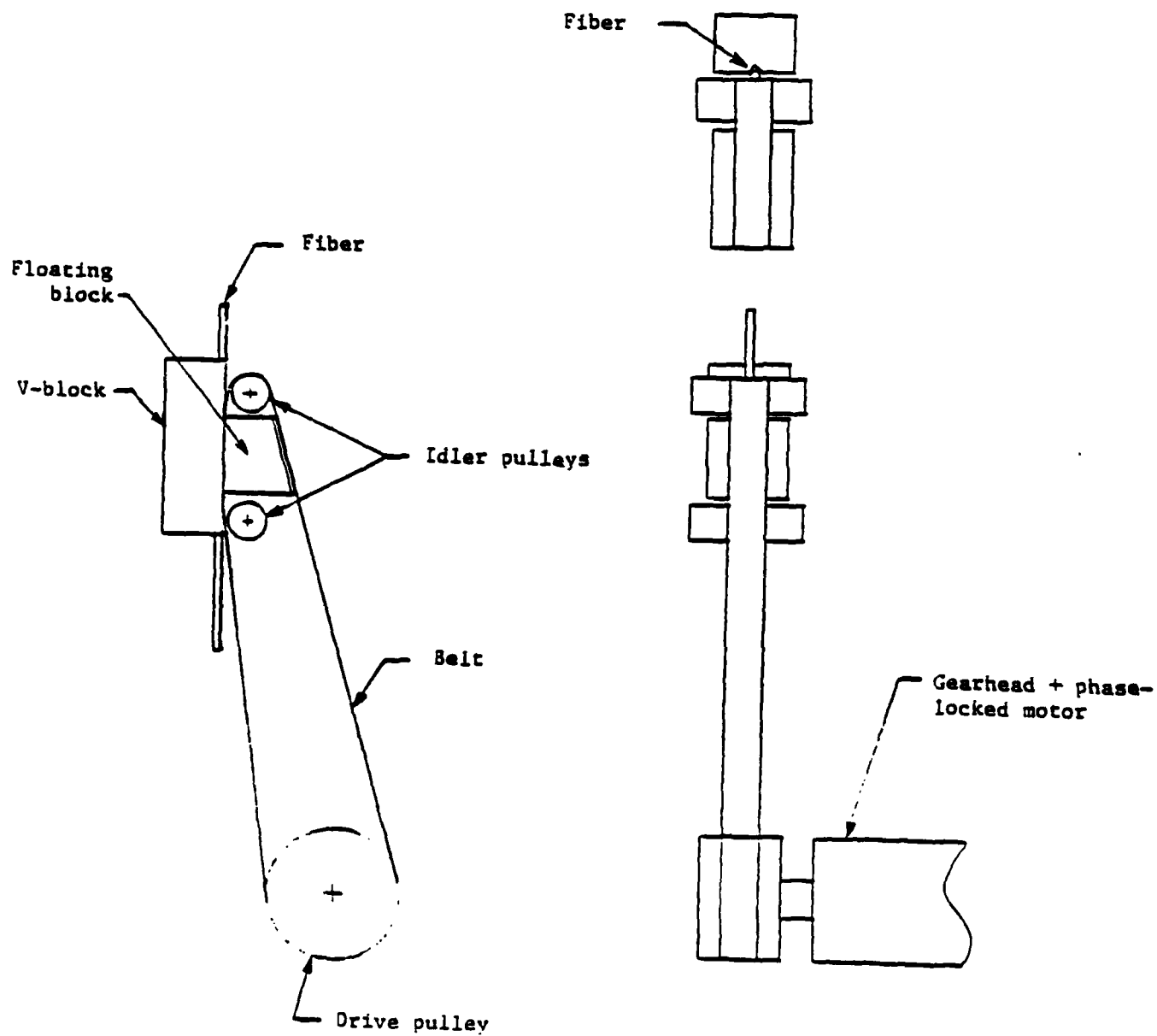


FIGURE 8

side-to-side wobble, and provides a smooth, hard sliding surface to allow uniform translation of the fiber along its axis. This design offers several advantages over the C.M.R. design:

- i. the fiber is supported at a fixed point in space, no matter how long the fiber, enhancing the mechanical stability of the growth zone,
- ii. the maximum fiber length is no longer limited by the length of a lead screw. A 5 cm long 0.5 mm diameter source rod could produce a 20 meter long 25 micron diameter fiber,
- iii. the controlled atmosphere chamber around the growth zone does not require mechanical feed-throughs,
- iv. the phase-lock system provides more accurate speed control than the analog control on the C.M.R. system.

A block diagram of the entire second generation system is shown in Fig. 9. The focusing system and fiber translation are enclosed in a controlled atmosphere chamber which isolates the molten zone from exterior perturbations and allows growth in inert gas, oxygen or vacuum environments. In order to permit adjustment of the fiber position with the chamber sealed, the fiber and feed rod translation devices are mounted on motorized x-y stages, not shown in the figure.

The heat source is a 15 watt waveguide CO<sub>2</sub> laser with active cavity temperature stabilization, chosen for its stable power and beam pointing and compact size. The laser output is monitored with a temperature stabilized pyroelectric detector with kilohertz response, allowing wide bandwidth stabilization of the laser power by modulating the tube current. An electro-optic amplitude modulator is used to attenuate the laser beam. The laser can

# FIBER GROWTH SYSTEM

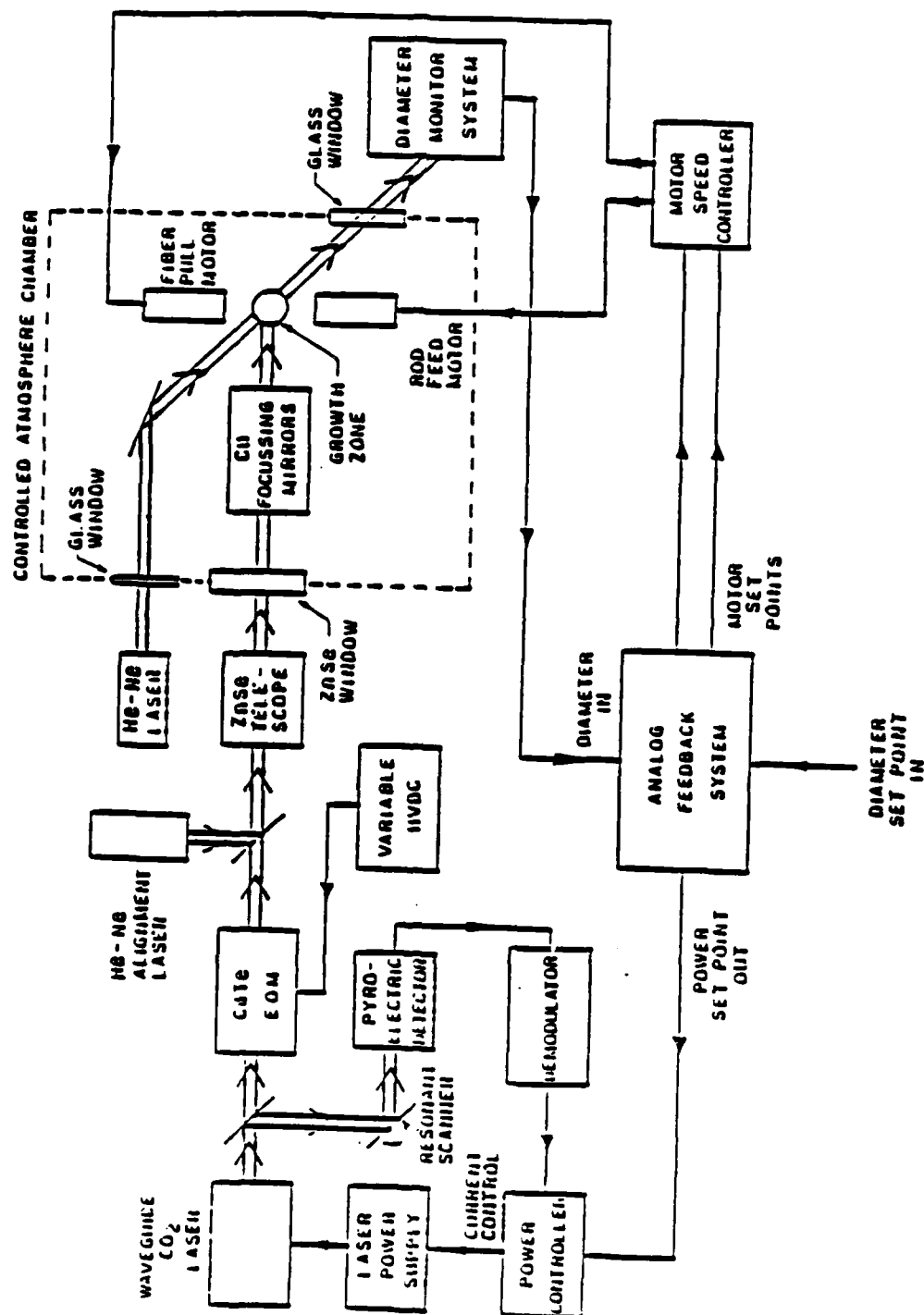


FIGURE 9

thus run at a constant output, enhancing power stability. An adjustable ZnSe telescope is used to vary the beam spot size input into the focusing optics, thereby varying the size of the focal spot at the fiber.

Another important feature of the growth apparatus is a high speed non-contact diameter measurement system. In order to provide a useful error signal for feedback control of diameter variations, the diameter measurement system must have a measurement rate  $\geq 1$  kHz, diameter resolution  $\geq 0.1\%$ , axial resolution as small as possible ( $\geq 5 \mu\text{m}$ ) and working distance  $\geq 100$  mm (to avoid obstruction of the  $\text{CO}_2$  focusing system). No commercial system was available meeting all these criteria, so we designed the system shown in Fig.10. A helium-neon laser beam illuminates one side of the fiber. The rays passing through the fiber and those reflected off the surface of the fiber interfere in the far field to form a series of light and dark fringes, whose period is inversely proportional to the fiber diameter. By imaging the interference pattern on a diode array and electronically tracking one of the fringes as it changes position in response to fiber diameter changes, one can derive a voltage proportional to the diameter change. As designed, the system has a resolution of 0.05%, an axial resolution of  $\sim 5 \mu\text{m}$  and a measurement rate of 1 kHz. The feedback system will be discussed later in this report.

2. System status. Mechanical and optical construction of the apparatus described in the previous section, with the exception of the diameter measurement system, was completed in the Spring of 1982. A series of equipment failures, to be discussed in more detail later in this report, delayed our making serious attempts to grow good quality fibers until June of 1983. Prior to that time, we were able to test and modify various elements of the system, so that progress has been rapid in the past month.

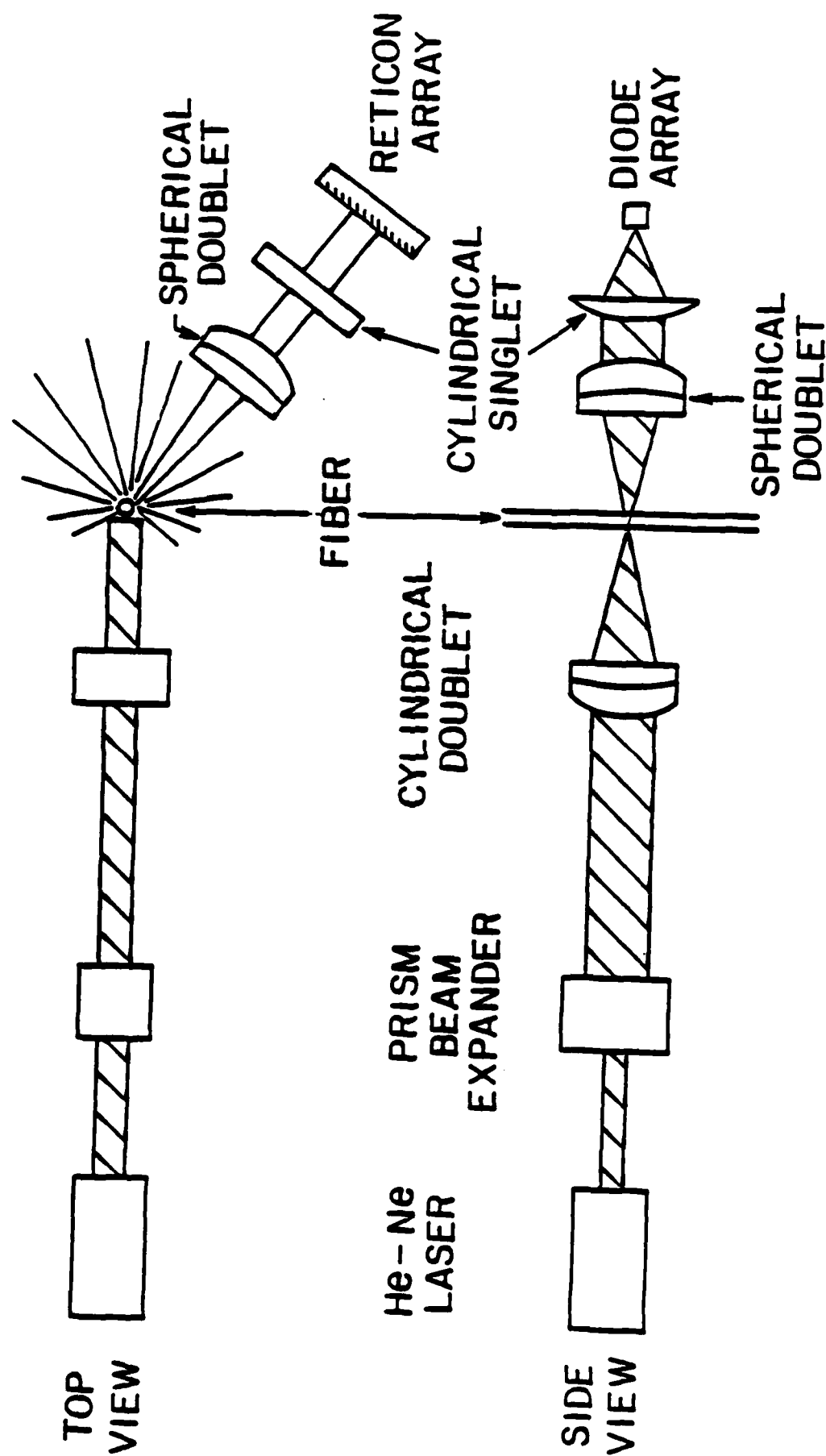


FIGURE 10

The commercial motor control system has unacceptable start-up transients, limited speed range and appreciable velocity jitter that the manufacturer has been unable to correct. We have obtained higher density shaft encoders and designed and built a more sophisticated control system. The motors now operate over a 100:1 speed range and start in  $\sim 100$  ms with no overshoot, performance more than adequate for our application.

We have also been able to study the performance of the fiber translation devices. The side-to-side motion of a fiber translated through the drivers appears to be limited only by the smoothness of the fiber itself. In the case of a smooth source rod, the wobble was measured to be less than three microns, the measurement resolution. The fiber velocity jitter is less than the measurement resolution of 3%.

The focusing system worked well in tests on melting lithium niobate and sapphire rods. The laser beam was focused symmetrically to a spot of less than 100 microns, the limiting resolution of measurement thus far. The efficiency of these optics is somewhat higher than those of the first generation system, leading to a reduction in the power necessary to reach melting temperature, particularly for small ( $< 200 \mu\text{m}$ ) fibers.

The beam handling optics and mechanical alignment adjustments all performed well in our tests. The electro-optic modulator cannot be tested until we obtain a laser with an  $\text{HE}_{11}$  output mode.

A prototype of the diameter measurement system was completed this Fall and performed up to design specifications described earlier except for the axial resolution which was  $\sim 12 \mu\text{m}$  instead of  $5 \mu\text{m}$ . This problem was traced to a defective lens which is being replaced by the manufacturer. Since this system has a combination of features not found in any other currently available

device, it may have commercial value. We are currently carrying out detailed characterization to complete an article describing the system.

We have obtained a long working distance 50 X binocular microscope and mounted it to observe the growth zone through a port in the controlled atmosphere chamber. In addition to its obvious utility in aligning the fiber with the optical system, the microscope video display can be used to study and record the growth dynamics of the crystal fibers. With a spike filter and line slicer, for example, the microscope video can be used to display a real time temperature profile of the melt zone, an important parameter for understanding the growth process.

Another recent addition to the growth effort is a centerless grinding machine, used to fabricate small diameter source rods of uniform cross-section. We have managed to grind rods of glass, YAG,  $\text{LiNbO}_3$  and  $\text{Li}_2\text{GeO}_3$  to diameters of 400 - 500 microns in lengths up to 12 cm, with a taper of less than 1 micron/centimeter. The small diameter of these rods gives us the ability to melt materials with higher melting points, and the uniform cross-section permits more stable growth than the 1 mm square rods used previously.

The fundamental difficulty thus far encountered has been the performance of the waveguide  $\text{CO}_2$  lasers. The laser had failures in its power supply and temperature control systems which we eventually repaired. However, a fundamental design flaw led to multi-transverse mode oscillation of the waveguide  $\text{CO}_2$  laser source. The manufacturer agreed to accept return of the laser for refund, and we have ordered a 15 W waveguide laser from another manufacturer, (California Laser). We have tested the mode quality of a California laser and found it to have a near perfect diffraction limited  $\text{HE}_{11}$  output, so we expect that the laser problems will be resolved on delivery of the new laser. Unfortunately, the laser has twice been damaged in shipping,

pushing back the delivery date from February 1983 to July 1983 (estimated).

The anticipated delay led us to adapt our system to accomodate a 20 watt sealed off CO<sub>2</sub> laser from China that happened to be available in our laboratory. It was necessary to modify the beam handling optics because the output beam of the Chinese laser is larger than that of the waveguide lasers. These modifications were completed in June of 1983. Progress has been rapid in fiber growth since that time.

We chose sapphire as our model material because its properties are well known, it is easy to grow, readily available and inexpensive. The basic manipulations involved in growing a fiber, e.g. loading fibers into the drivers, aligning fibers with the optical system, setting motor speeds, optimizing laser power, are all quite easy with this system. It is possible to complete the entire set up process and grow several centimeters of fiber in about thirty minutes.

In the past several weeks we have grown more than forty sapphire fibers, starting with 500 micron centerless ground source rods. In an effort to grow small diameter fibers we attempted to grow with a very large diameter reduction. We found it possible to reduce the fiber diameter by a factor of 4 but the growth process was quite unstable. Threefold diameter reduction, however, resulted in a very stable growth. The threefold diameter reduction compares favorably with the twofold reduction typically used on the C.M.R. machines.

Threefold diameter reductions have been obtained at growth rates between 0.5 and 5 mm/min. Lengths up to 10 centimeters of 170 micron fiber have been obtained. The necessary laser power is approximately 5 watts.

The quality of these fibers is substantially better than those grown at C.M.R. We are just beginning quantitative measurement of the diameter variations of the fibers. Preliminary results on one fiber indicate  $\sim 2\%$  peak-peak variations on a 5 mm section and  $\sim 2\%$  rms over longer sections. The remaining variations are at least in part due to a number of problems that exist with the Chinese laser. The high voltage power supply for the laser is not regulated, leading to fairly serious (several percent), power fluctuations. We have designed and recently installed a HV current regulator, and the several fibers since grown appear qualitatively to show less fine scale diameter variation. The laser is randomly polarized, which, in conjunction with some polarization sensitive dielectric turning mirrors, leads to further variation in the power delivered to the fiber. This problem will be difficult to eliminate until the new laser arrives. The large spot size and random polarization of the Chinese laser also preclude use of the detector for the closed loop power stabilization system. Given the limitations imposed by the present laser, the diameter variation results are very encouraging.

The modifications to the beam handling optics necessitated by the Chinese laser make it difficult to install the diameter measurement system, but we have obtained some qualitative information about the characteristic response lengths for diameter modulation. Both the decay length of starting transients and one preliminary experiment modulating the pull rate indicate that the diameter response will begin to roll off for modulation with a period less than  $\sim .5 - 1$  mm. The apparent reduction in 3-5 micron period variations when the laser current was regulated indicates that substantial modulation response to laser power extends to fairly short modulation periods.

3. The C.M.R. Growth Station. We are also continuing our cooperation with the Feigelson group at the Center for Materials Research at Stanford. They have grown several new technologically interesting materials in the past year and have made modifications to their system that have led to improved quality fibers.

One of the most important improvements to their system was the addition of an enclosure around the growth zone, eliminating the destabilizing effects of air currents. An attenuator system with three fixed levels and minimal beam walk and beam steering has been installed, to allow well above threshold operation of the laser even for small diameter or low melting point fibers.

An improved beam alignment system has also been installed, facilitating accurate focusing into the fiber. The effect of these modifications has been a considerable improvement in fiber quality. Nd:YAG fibers with diameters as small as 100 microns have been grown with diameter variations of several percent over centimeter lengths. These results are encouraging in their own right, but also suggest that the more sophisticated second generation system should produce usable fibers soon after being put into operation.

The C.M.R. group has recently taken delivery of a commercial diameter measurement system and is in the process of testing and installing it in their growth apparatus. Together with a mini-computer which they also have recently obtained, the diameter measurement instrument will form the basis of a closed loop diameter control system.

While the C.M.R. group has had its greatest success with Nd:YAG fibers, they have spent a considerable amount of time on growing fibers of a variety of materials. Among the more interesting are YIG, the first flux grown fiber,  $\text{Li}_2\text{GeO}_3$ , a material with large Raman cross-section that

we will discuss in more detail, and  $\text{Eu:Y}_2\text{O}_3$ , grown from a hot pressed ceramic source rod. This latter material suggests a useful application of this growth technique : the rapid growth of a variety of laser ion/host combinations for evaluation of their laser properties. The turn-around time of the process is such that several materials could be grown in a day, rather than one in a week as is common for conventional growth techniques. The hot press that will be delivered to C.M.R. in several months will facilitate the preparation of suitable source rods for these investigations.

Also planned for the near future is an electro formed nickel sphere to surround the growth zone and re-focus scattered  $\text{CO}_2$  light and black body radiation back onto the melt to facilitate growth of very high melting point materials and materials which do not strongly absorb the 10.6 micron  $\text{CO}_2$  radiation.

4. Fiber measurement activities. While our effort has focused on developing the means to grow good quality fibers, we have also been making preparations for experiments to be done after we obtain usable fibers. Last year's report discussed fiber characterization devices that we developed, including an index of refraction profiler, a device for mapping ferro-electric domain distributions and an interference microscope to measure the flatness of fiber ends.

In order to launch light efficiently into a fiber, it is necessary to illuminate the fiber with a clean Gaussian beam of the correct radius incident normal to a flat fiber end face. We have built a set of miniature gimble mounts for accurate angular positioning of the fiber and acquired a set of small x,y,z stages with differential micrometers for accurate translational positioning of the fiber. We have also listed a zooming beam expander which, in conjunction with a set of focussing lenses we already have

available, will allow continuous tuning of the laser beam waist to the optimum size for a given fiber. Our optics shop has developed a jig suitable for holding fibers rigidly during polishing, and has obtained fractional wave flatness across the faces of 100  $\mu\text{m}$  fibers.

We are also acquiring sources suitable for a variety of linear and nonlinear experiments in fibers. By refurbishing an old Chromatix YAG laser, we have access to cw, long pulse or Q-switched radiation at several infrared wavelengths in a clean  $\text{TEM}_{00}$  mode. An integral intracavity frequency doubling crystal shifts the laser output to red, yellow and green wavelengths. Our equipment list for next year includes an R.C.A. laser diode which supplies 40 mW in the near IR in a single transverse mode. We have also been in contact with researchers at Xerox, Palo Alto Research Center, who have provided us with a 200 mW phase locked laser diode array.

#### D. Future Research

In the coming year our primary goal is to overcome our equipment problems and obtain better quality fibers. Until the new laser arrives it will be difficult to grow fibers with diameters less than 160 microns. The unpolarized Chinese laser precludes the use of the electro-optic modulator to attenuate the laser beam, making the low powers necessary for the growth of small diameter fibers difficult to obtain. Instead, we will study the problems associated with growing longer fibers in the 160 micron diameter range, and continue qualitative investigations of the effects of pull rate and laser power modulation.

When the new  $\text{CO}_2$  waveguide laser arrives, it will be necessary to test it for mode quality, output power stability and beam pointing stability. Assuming it meets specifications, we can install it in our system and interface it to the wideband power stabilization. We hope to reach this point some time in July.

The next step will be quantitative evaluation of the transfer function between laser power or motor speed variations and the fiber diameter. Three pieces of equipment on next year's equipment list will be used for these measurements. A programmable frequency synthesizer will be used to generate a swept frequency to modulate the control parameter of interest. The output of the diameter measuring device will be input to the gain phase meter, as will the synthesizer output. The output of the gain phase meter will be output to the x-y recorder, directly plotting the open loop transfer function for the system. With the transfer functions available for a variety of combinations of growth conditions and fiber diameters, it will be possible to design compensation networks for a closed loop diameter stabilization system. Throughout this process the theoretical analyses developed for bulk float zoning will serve as a qualitative guide for interpreting our results. For well characterized materials like sapphire, quantitative comparison may be possible. As these procedures are all new and untried, it is entirely speculative to estimate a completion date for this stage of the project, but late Summer seems a reasonable guess.

At this point, or perhaps even before the closed loop control is implemented, we hopefully will be able to grow good quality fibers of our model material. We can then begin to characterize the linear properties of the fibers, e.g. mode launching, mode conversion, radiation loss, absorption loss. The Hamamatsu video system on this year's equipment budget will be very useful in this stage of the project. We would also investigate the effect of various glass and liquid claddings on the linear properties of the fibers.

Even before this process is complete we should be able to demonstrate interesting device applications of sapphire fibers. A high temperature one or two color pyrometer similar to that developed at N.B.S. could be demonstrated

in a flexible, all sapphire fiber configuration. High power transmission of an infrared laser beam, e.g. 200 W at 1.06 micron, could also be demonstrated. A simple polarizer could also be made by cladding a sapphire fiber with an isotropic material intermediate between sapphire's ordinary and extraordinary index of refraction.

The next material we grow after completing the sapphire model studies will be lithium niobate. At one point we had considered lithium germanate a likely candidate, primarily because its large Raman cross-section would make possible a demonstration of unphasematched stimulated Raman scattering in a fiber of moderate quality. While we have largely conquered the materials problems associated with handling and polishing fibers of this hygroscopic material, the difficulties entailed, together with the recent result from C.M.R. showing that small ( $\sim 150 \mu\text{m}$ ) c-axis  $\text{LiNbO}_3$  fibers grow single domain, have led us to choose lithium niobate.

We are particularly excited about the prospects for  $\text{LiNbO}_3$  nonlinear devices because we have recently acquired some niobate grown in China that does not exhibit significant index of refraction damage. This property greatly enhances the utility of the material for interactions involving visible wavelengths. We are studying the bulk and integrated optic waveguide properties of this 'damage free' lithium niobate in parallel with our efforts to complete the second generation growth apparatus. The possibility of periodically poling a lithium niobate fiber and the resultant 20 fold increase in nonlinear efficiency is enticing. We have obtained some  $40 \mu\text{m}$  thick lithium niobate plates and we are beginning to study poling these plates as a model system to design poling electrodes for fibers.

We have also recently begun a program to investigate the growth and spectroscopy of laser host ion combinations. One crystal of  $\text{Ti:A}\lambda_2\text{O}_3$  has already been obtained, and plans call for the study of a variety of combinations, including co-doped materials of the Cr:Nd:GGG family. The rapid turnaround time of the fiber growth process make it ideal for this type of survey.

Our goal is to fully characterize single crystal fibers, to use them to make both linear and nonlinear devices, and to study the properties of laser crystals. There continues to be a very strong interest in the possible devices allowed by single crystal fibers. Thus we continue to obtain direct and indirect support in this program from industry.

## V. PLASMA PUMPED INDIUM III VACUUM ULTRAVIOLET LASER STUDY

### A. Introduction

A basic idea for achieving short wavelength lasers is to work with multiply-ionized atoms. Such ions generally have larger energy differences between bound states than do neutral atoms having the same number of electrons. This is due to the increased potential of the more highly charged nuclei. The large energy gaps might be used to produce laser action at vacuum ultraviolet or even soft X-ray wavelengths. One method of producing highly ionized species is by photoionization using the energetic radiation produced in laser induced plasmas. We propose to demonstrate the feasibility of a laser of wavelength 1850 angstroms in doubly ionized indium vapor, using a laser induced plasma as a pump source. Isoelectronic scaling may permit shorter wavelengths in the next higher elements in the periodic table.

### B. Motivation for the Indium Study

Our interest in indium derives from the strong 4416 angstrom laser line in singly ionized cadmium (hereafter Cd II), and the principle of isoelectronic sequences. Ions of different elements having the same number of electrons are said to be isoelectronic, and the spectral structure of such ions are often quite similar. On this basis we might expect doubly ionized indium (In III) to exhibit the same structure which makes the 4416 angstrom transition in CdII a good four level laser. This expectation is confirmed by a variety of sources, including atomic energy level measurements,<sup>1</sup> computer calculations performed by us,<sup>2</sup> and literature reports of relative line strengths in the In III arc and spark excited spectra. Thus we are confident that the  $4d^{10} 5p^2 p_{3/2} \rightarrow 4d^9 5s^2 {}^2D_{3/2}$  transition in In III can be used to make a laser of wavelength 1850 angstroms, given an appropriate pumping mechanism. The mechanism we propose for populating the upper laser level is photoionization with black-body radiation from a laser induced plasma.

We hope to show that this technique is suitable for a whole class of lasers based on multiple photoionization pumping, which together with isoelectronic scaling will allow the extension of laser wavelengths deeper into the ultraviolet region.

When a high peak power pulsed laser is focused tightly onto a metal target, it produces a plasma so hot and dense that it radiates as a black-body in the vacuum ultraviolet and even soft X-ray regions of the spectrum. We believe that even though this radiation is of broad bandwidth, it can be used to selectively produce ions in excited states giving rise to laser action. A demonstration of this was recently carried out by Dr. William Silfvast of Bell Laboratories.<sup>3</sup> Silfvast used radiation from a plasma created with a 1 joule Nd:YAG laser pulse to photoionize 4d electrons from neutral Cd I atoms in a vapor. This directly populated the  $4d^9 5s^2 {}^2D$  upper laser level of the 4416 angstrom transition in Cd II. Very strong laser action at 4416 angstroms was obtained in this experiment.

Our calculations using photoionization cross-sections for indium indicate that the radiation from a laser induced plasma can selectively remove the 5p and a 4d electron from neutral indium atoms (configuration  $4d^{10} 5s^2 5p$ ) to produce the  $4d^9 5s^2 {}^2D$  excited state in In III. This excited state is expected to produce laser action at 1850 angstroms by the two electron transition to  $4d^{10} 5p {}^2P$ .

An important part of our indium experiments will be spectroscopic measurements on In III which to our knowledge have not been made before. For example, we will measure the radiative lifetime of the  $4d^9 5s^2 {}^2D_{3/2}$  excited state of In III, and perhaps lifetimes of other levels accessible from this level by laser probes. These measurements, together with

spectroscopic information already known for Cd II, could help improve ab initio atomic structure calculation methods. The  $4d^{10} 5p^2 P \rightarrow 4d^9 5s^2 {}^2D$  transition is of particular interest because the oscillator strength of this surprisingly strong two electron transition comes purely from configuration interaction. Experimental measurements on this transition will help to test present multi-configuration Hartree-Fock (MCHF) methods for atomic calculations and may suggest improvements needed for this method.

### C. Proposed Experiments

In our first experiments, we propose to produce a cloud of ground state In II ions by ablation of a liquid indium target using a CO<sub>2</sub> TEA laser. The density of this cloud can be probed by the curve of growth absorption technique<sup>4</sup> on either the 1586 angstrom resonance line or the 2307 angstrom inter-combination line. Then Nd:YAG laser pulses will be tightly focused onto a tantalum target, providing the VUV radiation necessary to photoionize a 4d electron from the In II ions. This will produce population in the upper level of the proposed 1850 angstrom laser scheme. By measuring the fluorescent lifetime of this level, we can determine the oscillator strength of the transition. This can be compared to ab initio values calculated by the MCHF method. Measurements of the fluorescent power output can then be used to determine the population density of ions in the upper level of the 1850 angstrom transition. This in turn allows a calculation of the 4d photoionization cross-section (integrated over the laser induced plasma black-body spectral distribution) for In II.

We estimate that laser action can likely be obtained in this experiment using 1 joule pulses from a Nd:YAG laser to create the laser induced plasma radiation source, and 1 joule pulses from a CO<sub>2</sub> TEA laser to generate the In II vapor by ablation of an indium target.

As a second stage of experiments, we plan to start with neutral indium vapor and perform both of the required ionization steps using only the black-body radiation from a laser induced plasma. It is judged unlikely that the In III 1850 angstrom laser can be successfully pumped with only 1 joule Nd:YAG pulses, but Nd:Glass amplifiers might produce enough energy to pump the laser. More important will be the demonstration of the ability to selectively populate the upper laser level using only broad band radiation from a laser induced plasma.

There are many additional experiments that might evolve from this study. The creation of substantial populations of the  $4d^9 5s^2 {}^2D$  level of In III, which lies  $\sim 12,000 \text{ cm}^{-1}$  above ground state, will make many other excited states accessible by absorption of visible or long wave UV light from tunable dye lasers. These more highly excited levels may prove useful as upper levels for other laser wavelengths, or for generation of short wavelength light by anti-Stokes Raman scattering from the  $4d^9 5s^2 {}^2D$  level.

Central to all of these experiments is the strong source of VUV radiation provided by laser induced plasmas. The generation of such plasmas requires high ( $\sim 10^{12} \text{ watts/cm}^2$ ) intensities of laser light delivered to the plasma forming target. The plasma forming laser must, therefore, have high spatial mode quality, so that it can be focused to very small ( $\sim 10 - 100 \text{ }\mu\text{m}$ ) spot sizes. In addition, the laser energy must be very stable, as the temperature of the laser induced plasma is highly nonlinear with respect to the intensity of the laser. We have found that the Quanta Ray model DCR-2A Nd:YAG laser has the necessary qualities for this work. It is also ideally suited for pumping the pulsed dye laser which we already have in our laboratory, and which may be needed in these proposed experiments.

1. Charlotte E. Moore, Atomic Energy Levels, vol. III, National Standard Reference Data Systems.
2. Calculations performed using the multiconfiguration Hartee-Fock code "MCHF83", by Charlotte F. Fischer, Computer Science Department, Vanderbilt University.
3. Personal communication, June 1983.
4. Anne P. Thorne, Spectrophysics, Chapter 10.

## VI. FUTURE DIRECTIONS

Our recent progress in slab geometry laser sources has opened new areas of research in the vacuum ultraviolet and X-ray spectral regions. Our next generation slab glass laser source is designed to operate as a glass oscillator/amplifier at 10 J per pulse at 10 pps or 100 W of average power. The peak power is designed to be 5 GW in a 2 nsec pulse length. When focused to 50  $\mu\text{m}$  spot size, an optimum for plasma excitation, the peak intensity on target is  $2.6 \times 10^{14} \text{ W/cm}^2$ . At this intensity more than 40% of the 1.05  $\mu\text{m}$  radiation is absorbed and re-radiated as broad band X-ray emission. We thus have access to a point X-ray vacuum ultraviolet source of more than 10 W of average power.

Applications for the source include X-ray lithography, X-ray microscopy, X-ray Raman spectroscopy, X-ray XAFS spectroscopy and X-ray pumping of coherent sources.

It is already clear that the laser plasma soft X-ray source is an important supplement to the well established synchrotron radiation source. The next generation high peak and average power slab lasers make this approach to the production of X-rays very competitive to alternative but better known sources.

We plan to exploit our slab laser capability for X-ray generation, characterization and applications over the next graduate student generation.

## VII. PUBLICATIONS AND CONFERENCE PAPERS

1. R.L. Byer and M. Endemann, "Remote Measurements of Trace Species in the Troposphere", Presented as Paper 81-0377 at the A.I.A.A. 19th Aerospace Sciences Meeting, St. Louis, MO. January 1981, A.I.A.S. vol. 20, #3, March 1982.
2. D.C. Wolfe and R.L. Byer, "Model Studies of Laser Absorption Computed Tomography for Remote Air Pollution Measurement", Applied Optics, April 1982.
3. M. Endemann and R.L. Byer, "Simultaneous Remote Measurements of Atmospheric Temperature and Humidity Using a Continuously Tunable IR LIDAR", Applied Optics, vol. 20, #18, p.3211 (15th September 1982).
4. R.L. Byer, T.J. Kane, J. Eggleston and Sun Yun Long, "Solid State Laser Sources for Remote Sensing", published in Technical Digest, Paper given at the Monterey, California, Workshop on Optical and Laser Remote Sensing, held in February 1982, Paper H2.
5. F. Koenig, P. Oesterlin and R.L. Byer, "Coherent Anti-Stokes Raman Scattering (CARS) of Large  $C_2H_4Ar$  Clusters", Chem. Phys. Letts. vol. 88, #5, p.477 (21st May 1982).
6. J.C. McDaniel, D. Baganoff and R.L. Byer, "Density Measurement in Compressible Flows Using Off-resonant Laser Induced Fluorescence", Am. Inst. of Phys., Phys. Fluids 25(7), p.1105 (July 1982).
7. J.M. Eggleston, T.J. Kane, J. Unternahrer and R.L. Byer, "Slab Geometry Nd:Glass Laser Performance Studies", Optics Letters, vol. 7, #9, p.405 (September 1982).
8. Sun Yun Long and R.L. Byer, "Sub-megahertz Frequency Stabilized Nd:YAG Oscillator", Optics Letters, vol. 7, #9, p.408 (September 1982).

9. E.K. Gustafson, J.C. McDaniel and R.L. Byer, "High Resolution Continuous Wave Coherent Anti-Stokes Raman Spectroscopy in a Supersonic Jet", *Optics Letters*, vol. 7, #9, p.434 (September 1982).
10. M. Fejer, R.L. Byer, R. Feigelson and W. Kway, "Growth and Characterization of Single Crystal Refractory Oxide Fibers", *S.P.I.E. vol. 320, Advances in Infrared Fibers II*, p.50 (1982).
11. R.L. Byer, T. Kane, J. Eggleston and Sun Yun Long, "Solid State Laser Sources for Remote Sensing", published in Optical and Laser Remote Sensing, (Springer Series in Optical Sciences), ed. D.K. Killinger and A. Mooradian, p. 245. Springer-Verlag.
12. K. Bennett and R.L. Byer, "Variable Laser Attenuators - Old and New", published in Laser Focus, vol. 19, #4, p.55 (April 1983).
13. J.M. Eggleston, T. Kane, K. Kuhn and R.L. Byer, "Progress in Slab Geometry Solid State Lasers", published in the Proceedings of S.P.I.E. vol. 335, Advanced Laser Technology and Applications, (S.P.I.E. Conference, May 1982, in Arlington, Virginia).

#### CONFERENCE PRESENTATIONS:

1. R.L. Byer, T. Kane, J. Eggleston and Sun Yun Long, "Solid State Laser Sources for Remote Sensing", presented at the Workshop on Optical and Laser Remote Sensing, held in Monterey, California, February, 1982.
2. J.M. Eggleston, T. Kane and R.L. Byer, "Slab Geometry Solid State Lasers", C.L.E.O. Conference, held in Phoenix, Arizona, April 1982.
3. T. Kane, J. Eggleston and R.L. Byer, "Polarized cw Nd:YAG Laser Using a Slab Geometry", C.L.E.O. Conference, held in Phoenix, Arizona, April 1982.

4. J. Eggleston, T. Kane and R.L. Byer and J. Unternahrer, "Slab Geometry Solid State Lasers", I.Q.E.C. held in Munich, Germany, June/July 1982.
5. T. Kane and R.L. Byer, "A Proposed Kilowatt Average Power Nd:Glass Laser", Paper WE2, Optical Society of America Conference, held in Tucson, Arizona, October 1982.
6. K. Kuhn, T. Kane and R.L. Byer, "Conductive Cooling of Slab Glass Lasers", Paper WE3, Optical Society of America Conference, held in Tucson, Arizona, October 1982.

#### INVITED PAPERS AND SEMINARS:

1. R.L. Byer "Alternate Sources of Funding in Physics", AAAP/APS, San Francisco, California, January 1982.
2. R.L. Byer "Progress in Slab Configuration Lasers", Naval Research Laboratory, February 1982.
3. R.L. Byer "Solid State Laser Sources for Remote Sensing", Workshop on Optical and Laser Remote Sensing, Monterey, California, February 1982.
4. R.L. Byer "Laser Sources for Combustion Diagnostics", Air Force Symposium on Combustion Diagnostics, Stanford, California, February 1982.
5. R.L. Byer "Slab Geometry Lasers", S.P.I.E. Meeting, Washington D.C. May 1982.
6. R.L. Byer "Laser Sources for Remote Sensing", National Bureau of Standards, D.O.D. Conference on Chemical Detection Methods, July 1982.

7. R.L. Byer "Progress in High Resolution Raman Spectroscopy"  
Physics Department Colloq. University of Toronto,  
Canada, September 1982.
8. R.L. Byer "High Power Solid State Slab Geometry Lasers", T.R.W.  
October 1982.
9. R.L. Byer "Progress in CARS Spectroscopy" and "Recent Advances  
in Solid State Lasers", presented at Tsinghua University,  
and Shanghai Laser Institute, China. November, 1982.  
(Member of IEEE Delagation to China).
10. R.L. Byer "High Resolution cw CARS Spectroscopy", Western Spectroscopy  
Association Conference, Asilomar, California, January 1983.
11. R.L. Byer "Material Aspects of Solid State Lasers", Seminar at  
Material Science Department, Stanford University.
12. R.L. Byer "Advances in Lasers", Industrial Affiliates Meeting,  
Chemistry and Physics Department, Stanford University,  
February 1983.
13. R.L. Byer "Slab Geometry Lasers", Norwegian Optical Society Meeting,  
Oslo, Norway, March 1983.

#### VIII. INTERACTIONS WITH GOVERNMENT AND INDUSTRY

Our research program continues to involve heavy industrial and government laboratory contact.

Our research in laser ionization mass spectroscopy has been of interest to Atom Sciences, a small private company in Tennessee. The United States Army and Air Force have also benefitted from our study in review of new technologies that may assist in chemical agent detection.

Our research in single crystal fiber growth has been of intense interest to industry for a variety of potential uses. Companies directly interested include General Motors for engine sensing, Westinghouse for turbine sensing, Xerox for diode laser harmonic generation, I.B.M. for laser spectroscopy studies, Livermore National Laboratories for laser host ion studies.

Our recent work in laser plasma X-ray production has been under close scrutiny by Hewlett Packard, Bell Telephone Laboratories and I.B.M. We expect to obtain industrial support in the future for research in this area.

IX. PROFESSIONAL PERSONNEL ASSOCIATED WITH THE PROGRAM

A. Graduate Students:

Bob Lacy is a fifth year student responsible for indium studies,

Marty Fejer is a fifth year student who has designed and constructed the fiber growth machine. A patent was recently issued for the machine.

John Nightingale is a fourth year student also responsible for the single crystal fiber machine.

Alan Nilsson is a second year student interested in laser plasmas as a unique spectroscopic source.

B. Visitors:

Robert C. Eckardt visitor from the Naval Research Laboratories for one year. He will join the Byer group in September 1983 as a Senior Research Associate.

C. John Eggleston graduated with a Ph.D. in June 1983. He is a Staff Scientist at Mathematical Sciences, N.W.

**END**

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